1985

Estimation of body segment parameters of college age females using a mathematical model.

Carol Ann. Finch
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ESTIMATION OF BODY SEGMENT PARAMETERS OF COLLEGE AGE FEMALES USING A MATHEMATICAL MODEL

by

Carol Ann Finch

A Thesis
submitted to the
Faculty of Graduate Studies and Research
through the Faculty of
Human Kinetics in Partial Fulfillment
of the requirements for the Degree
of Master of Human Kinetics at
the University of Windsor

Windsor, Ontario, Canada

1985

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ABSTRACT

ESTIMATION OF BODY SEGMENT PARAMETERS

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The purpose of this study was to determine the body segment parameters of college age females of three different body types, and establish three complete sets of body segment parameter data for these populations.

Fifteen subjects were somatotyped using the Heath-Carter method and deemed as being either endomorphic, mesomorphic or ectomorphic. Once classified, subjects were photographed, with relevant anatomical landmarks and joint centers marked, in two planes (x-z, y-z).

The Jensen, photogrammetric mathematical model was used to determine segmental masses, lengths, center of gravity locations and proximal/distal radius of gyration locations about each of the three principal axes. These segment parameter data were presented in percent ratio form.

The overall accuracy of the model for determining total body mass of females was found to be better than 99%.

Similarly, sufficient congruency was evident between pre-established norms and model-predicted parameters to further establish the credibility of the model.

Some significant differences in parameter values were revealed between the endomorph, mesomorph and ectomorph body types. These differences occured primarily in the computed percentage values of segment mass and radius of gyration about the longitudinal axis. The observed differences principally existed between the endomorph/ectomorph and endomorph/mesomorph groups.

The results of this study have important implications for future biomechanics research on females. The established credibility of the Jensen model make it a viable option for estimating the body segment parameters directly from female subjects. In situations when the direct application of the model is not feasible, the use of the newly generated body segment parameter ratio values is recommended. These three sets of data fill the void which existed in terms of data on females of different body types, and provide values for radius of gyration about the longitudinal axes not available from other sources.

ACKNOWLEDGEMENTS

I would like to thank Drs. Leavitt and Taylor for their time and effort spent while serving in my thesis committee.

Appreciation is also extended to Dr. Hermiston for sharing his computer expertise with me.

Special thanks goes to Dr. Jensen of Laurentian University for providing the computerized mathematical model and for making himself available to answer my questions.

Last, but certainly not least, I wish to sincerely thank Dr. Wayne Marino for the guidance and support he gave during this project, and throughout my academic career at the University of Windsor. Thank you for having confidence in me.

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Chapter 1

INTRODUCTION

In order to better comprehend human movement, human kineticists, or more specifically those in the field of biomechanics, study the forces which initiate, alter and stop motion of a body under investigation. A complete kinetic analysis of this nature requires that such properties as torque, force, momentum and kinetic energy be calculated. These kinetic properties are derived from a combination of kinematic and inertial parameters. Kinematic characteristics may be obtained in a variety of ways, one of the most common is through film analysis. Unfortunately, inertial properties are not as easily obtained. Such properties as segmental masses and weights, segmental centers of gravity, radii of gyration and moments of inertia may, in certain instances, be obtained directly, however the techniques are tedious and time consuming. Hence researchers rely on body segment parameter data for the determination of these inertial properties. The combination of direct measures, such as total body mass/weight and segmental lengths, with body segment parameter data yields the inertial properties necessary to calculate the kinetic properties of motion.

Statement of the problem

The purpose of this study was to determine the body segment parameters of college age females of three different body types, and establish three complete sets of body segment parameter data for these populations. The Jensen (1976) mathematical model was utilized for these purposes. The initial subproblem was to establish the accuracy of the chosen mathematical model for use with female subjects. The final subproblem addressed was whether significant differences existed between the three body typed groups of females on each of the model predicted parameters, thus warranting the generation of the three sets of data.

Hypotheses

The initial hypothesis tested was whether the "model predicted" parameters were significantly different from criterion values. The accuracy of the model for determining body segment parameters would be considered good if the null hypothesis failed rejection at this level. The alternate hypothesis was that there were significant, unexplainable differences between the calculated inertial parameters and those selected as the criteria. Acceptance of this hypothesis would lead to the overall rejection of the body segment parameter values calculated from the mathematical model.

If the model predicted parameters were found to be accurate, subsequent hypothesis testing between the groups would ensue. The null hypothesis stated that there would be no significant differences between the groups on selected inertial parameters. The alternate hypothesis stated that there would be significant differences between the body segment parameter values of the three different body type groups of women.

Assumptions

There were a number of assumptions made before developing a mathematical model of the human body. Simply stated, the body consisted of a limited series of linked masses; the masses were linked at pivotal points which had a limited number of degrees of freedom; the joints were frictionless and pinned; the masses were internally stable, rigid and homogeneous (displacement of blood and soft tissue was disregarded); and the masses could be closely approximated by simple geometric forms (Miller and

Nelson,1973; Clauser et al,1969).

The Jensen (1976,1978) mathematical model, the model of choice, was based on the assumption that the body was composed of two centimeter wide, horizontal elliptical zones of known, uniform density. The segmental density values presented by Clauser et al (1969) were assumed to be valid for the particular sample under investigation. This assumption of known density was dictated by current knowledge. The assumption of homogeneous, or uniform, body density was a simplifying one that enabled the mass centroid location to be equated with the volume centroid location.

It must be assumed that the segmental boundaries could be accurately delineated, also, that the joint centers could adequately be represented by a single point chosen from external landmarks.

By assuming mathematically that the body model was rearranged symmetrically about the sagittal and frontal planes, the moments of inertia calculated were the principal moments (Jensen,1981b). Similarly because the body segments were assumed to be perpendicular to the optical axis of the camera, digitization of segment lengths, except the feet, could be made directly from the frontal view photograpgh (Hall and Depauw, 1982).

The assumption of bilateral symmetry was made in order to minimize the required digitizing time.

It was assumed that the criterion for classifying body types as representative of either endomorphic, mesomorphic or ectomorphic was stringent enough to produce noticable differences in the body morphologies between the subjects.

Finally, the criteria that was used to establish the accuracy of the model were assumed to be valid.

Definition of Terms

Archimedes principle-- A law of fluid mechanics which states that the weight loss on immersion equals the weight of the displaced water which equals the volume.

Center of Gravity-- The point through which the resultant of all mass particles in the body pass.

Density-- The ratio of the mass of an object to its volume. This term is used interchangeably with specific gravity-- the ratio of the mass of a given volume of a substance to that of an equal volume of water.

Dimorphism-- The difference (as of form or size) between two individuals that might be expected to be similar or identical.

Ectomorphy-- The degree to which an individual physique shows characteristics of linearity.

Endomorphy-- The degree to which an individual physique shows characteristics of fatness.

Mass-- The quantitative measure of a body's inertia.

Mesomorphy-- The degree to which an individual physique shows characteristics of musculoskeletal robustness.

Moment of Inertia-- The measure of a body's resistance to changes in angular acceleration. This takes into account the body's mass and how that mass is distributed relative to the axis of rotation.

Oscillation period-- In a free swinging pendulum system, the moment of inertia can be calculated by applying the formula $Io = WL/4\pi^2 f^2$ where W=weight; L=distance from the center of gravity to the point of suspension; f= frequency of oscillation.

Parallel axis theorem-- A theorem which states that the moment of inertia with respect to any axis parallel to one through the mass center is equal to the product of mass and the square of the perpendicular distance between the parallel axes.

Principal axes-- A set of three orthogonal axes whose origin is always at the center of mass and whose orientation remains fixed with respect to the axis system of the elliptical cylinder. These axes are the X (frontal), Y (transverse), and Z (longitudinal) axes of the body.

Principle of lever moments-- A law which states that the sum of the moments is equal to the moment of the sum.

Principal planes-- The sagittal plane bisects the body into left and right, the frontal plane bisects the body into anterior and posterior, and the transverse plane bisects the body into inferior and superior.

Radius of gyration-- The distance from the axis of rotation to an assumed point where the concentrated total mass of the body would have the same moment of inertia as it does in its original distributed state.

Somatotype-- A physique classification based on the concept of shape or outer conformity of body composition, disregarding size. The classification system involves the evaluation of each of the three components, (endomorphy, mesomorphy, ectomorphy), on a rating scale.

Volume-- The amount of physical space a body occupies.

Delimitations

Several limitations under experimentor control were imposed on this study. Included in these delimiting factors were the sampling procedure employed and the relatively small and select sample chosen. In making the assumption of bilateral symmetry, the sample representativeness was further delimited.

The criterion selected for classifying subjects according to body type and for establishing the accuracy of the calculated values may have also delimited the results.

Final delimitations imposed and recognized were the prediction accuracy of the modelling technique, the inability of the model to account for assymetrical locations of internal organs and the simplifying assumption of uniform density.

Limitations

The accuracy with which the joint centers and segmental boundaries were located and delineated, possibly imposed a limitation on the study. Similarly, any shifting of the markings over the skin as movement occured, could confound the results. Other uncontrollable factors concerning the accuracy in locating reference points included the visual acuity, eye-hand co-ordination, judgement and consistency of the researcher. These aforementioned limitations may have ultimately affected the reliability of the data analysis.

Finally, the problems associated with applying cadaver density values to living populations imposed further limitations on this study. These limiting factors are discussed in detail in the Review of Literature.

Chapter II

REVIEW OF THE LITERATURE

The size and inertial parameters which define the human body segments have been of interest to many researchers over the past 120 years. The methods used to obtain or estimate these parameters are often diverse in nature. Hence, some form of classification is warranted and indeed exists. According to Miller and Nelson (1973), the estimation of such segmental parameters falls into three principal classifications : cadaver studies, techniques used on living subjects and mathematical models.

Cadaver Studies

The value of cadaver studies lies in their potential for providing a basis for prediction of segmental parameters in living subjects (Miller and Nelson,1973). The earliest reported work concerned with body segment parameters was that of Harless (1860). Two male executed criminals were dismembered into 18 major segments in order to determine segmental weights and locations of the centers of gravity along the long axis of the segments. Tissues were severed in a plane that bisected the primary center of joint rotation and the joints were disarticulated. The center of gravity location was determined using a balance plate. Sensitive scales were used to obtain segmental weights. Using an assumed density of 1.066, segmental volumes were calculated. Subsequently, 44 extremities from 7 corpses were weighed and the volumes calculated using Archimedes principle. Harless concluded that age and sex were significant factors in explaining the distribution of values of the specific gravity of the body segments.

Braune and Fisher (1886) increased the number of cadavers studied to five by dissecting three male suicide victims. In order to minimize fluid loss, a problem encountered by Harless, the cadavers were kept frozen throughout the investigation. This, however, prohibited dissecting out the joints, thus they sawed directly across the joints at their approximate centers of rotation. Total body and segmental mass center locations were determined using a more accurate hanging technique than the previously used balance plate. Three rods were used to hang the segment along each of its principal axes, thus allowing the center of mass to be more accurately determined.

Using similar techniques as Braune and Fisher (1886), Fisher, (1906) dissected a single male cadaver and reported segmental weights, masses and centers of mass. Also computed were values of the segmental moments of inertia. This work appeared to be the first of its kind in dealing with segmental moments of inertia.

Dempster (1955) in a classic study, perfected and standardized research techniques in the area of body segment parameter data. Eight male cadavers were used, all specimens were older and smaller, in terms of height and weight, than the average white male in the population. Physically however, the subjects were representative specimens for their age level (Dempster,1955). The joints were frozen at mid-position and bisected by cuts through the joint centers. Dempster felt that cutting through straight or fully flexed joints would place a portion of mass properly belonging to one segment more or less into the next. Thus, the mid position provided a more reasonable compromise as to the separation of the masses (Dempster,1955). Segmental masses were determined on weigh scales and segmental center of gravity locations were determined on a balance plate. In order to determine the moments of inertia, the oscillation period was determined on a free-swinging pendulum system. The final parameter determined was the segmental volume. Segments were thawed and immersed in water and following Archimedes method, volumes were determined. Dempster's data is the most widely cited and comprehensive investigation of body segment parameters.(Miller and Nelson,1973).

Clauser et al. (1969) felt there was a need to increase the sample of cadavers studied thus they dissected thirteen male cadavers. Their subjects more closely approximated the wide range of physical body sizes found in the normal population. The cadavers were dismembered into 14 segments by dissecting along a plane through the center of rotation. Clauser found it impossible to flex the joint to mid-range, as Dempster (1955) had done, thus bony landmarks were established and used as reference points to allow accurate segmental cuts. Similar procedures as Dempsters (1955) were used for the determination of center of mass, volumes and weights of the segments.

The difficulty of acquiring large representative samples of populations for dissection is evidenced by the fact that over the past century the body segment parameters of fewer than fifty cadavers have been studied (Miller and Nelson,1973). Furthermore, the question of whether or not the cadaver population is representative of the living casts doubt upon the usefulness of cadaver data. Clauser et al. (1969) point out several limiting factors when considering the applicability of cadaver data to living populations. Pre and post mortem wasting of body fluid, tissue losses during segmentation, gained or lost unknown quantities of water in the hollow viscera and/or loss of blood could all contribute to errors during the calculation of body segment parameters of cadavers. Also, because of the lack of understanding of changes in tissue and body fluids at death, even cadaver samples that are similar to living populations may not be representative in terms of the segment parameters. Finally, because the sample of cadavers has been restricted to older male caucasians, the suitability of their use for other populations must be questionned.

Techniques with Living Subjects

The second of the three principal classifications for the estimation of segmental parameters are techniques with living subjects. The advantage of such techniques over cadaver data is obvious, however inherent in each are limitations. Some, while appearing to be theoretically sound, are restricted in application to only a few body segments; others require an excessive amount of time for data collection, require complicated data reduction, need expensive equipment or are simply not administratively feasible (Miller and Nelson,1973). Although by no means exhaustive, the following techniques are available for the determination of body segment parameters in living subjects : immersion, mensuration, reaction change, quick release, pendulum, torsional pendulum, radiation and computation.

Immersion techniques are used to determine segmental volumes and subsequently segmental mass, as mass is the product of density and volume. This technique is well suited for the determination of volume of the extremities, not so well suited for the trunk and head (Miller and Nelson,1973). Immersion has been used extensively by researchers (Dempster,1955; Kjeldsen,1972; Johnson,1976; Plagenhoef,1963), often serving as the criterion method for comparison with obtained volume estimates from other techniques (Katch et al.,1974; Katch and Weltman, 1975; Sady et al.,1978; Freedson et al.,1979; Hatze,1980).

Other methods for the determination of segmental volumes include mensuration and photogrammetry. According to Contini (1972), a relatively good approximation of segmental volumes can be obtained by using circumferential measurements at certain selected stations on the segment and the linear dimensions between any two consecutive circumferential measurements. This technique, mensuration, is outlined in detail elsewhere (Contini,1972). The basic notion underlying photogrammetry is essentially that used in developing contour maps in aerial photography (Contini et al.,1963). Two methods exist, mono- and stereo-photogrammetry, neither has been used widely to collect body segment parameter data (Miller and Nelson, 1973). Specific details of these procedures are outlined elsewhere (Contini et al.,1963).

The reaction change method allows the determination of either segmental weight or segmental center of gravity location, however not both. This technique has also been used to determine total body center of gravity location (Page,1974; Squire,1977; Hall and Depauw,1982). Reaction change, which is based on the principle of lever moments, is discussed in detail elsewhere (Drillis et al.,1964; Contini,1972; Miller and Nelson,1973).

The quick release technique allows the estimation of segmental moments of inertia with respect to a horizontal axis passing through a proximal joint (Miller and Nelson,1973). This method is based on Newtons law for rotation: the torque acting on a body is proportional to its angular acceleration; the proportionality constant being the mass moment of inertia (Drillis et al.,1964). Stijner et al. (1981) presented a modified release method which produced results that were highly reproducible.

Two alternate methods are available for calculating moments of inertia, the compound pendulum and torsional pendulum techniques. Details of these methods, both of which are based on the oscillating pendulum idea, are provided by Drillis et al. (1964).

Miller and Nelson (1973) discussed the radiation technique as a way to determine body segment parameters in living subjects. The procedure involves focussing high energy gamma rays onto a selected object. As the transmission of photons is related to the mass of the object, the number of rays which penetrate provide a basis for evaluating its mass (Miller and Nelson,1973). With the development of x-ray computerized tomography, it is now possible to obtain outlines of body structures and their constituents (Huang and Suarez,1983). Indeed, Huang and Suarez (1983) used this method to evaluate the cross-sectional geometry and mass density distribution of both humans and laboratory animals. They found their procedure was feasible for determining mass, volume, specific gravity, location of the center of gravity and the moments of inertia for the segments of interest.

Computational procedures, or the method of coefficients, allow the calculation of inertial properties of a body segment by assuming a fixed relationship between total body weight and segment weight, and between length of a segment and the location of the center of gravity or radius of gyration. Similarly, inertial properties may be determined from a linear combination of predictors. Indeed Barter (1957) compiled the work of Braune and Fisher (1886), Fisher (1906) and Dempster (1955) and developed a series of regression equations for predicting segmental weights from body weight. Likewise, Clauser et al (1969) developed multiple regression equations for predicting segmental weights, volumes and centers of gravity from a combination of body weight and two or three anthropometric variables. Katch et al. (1974) provided multiple linear regression equations using anthropometric data to predict criterion segment volumes in women. Details of their procedure, the segment zone approach, is discussed in a subsequent section. Zatsiorsky and Seluyanov (1981) provided multiple regression equations to estimate segment mass, segment center of gravity location and segmental moments of inertia about each of the three principal axes with the knowledge of total body height and weight. The equations were developed from data collected on 100 male subjects using the gamma radiation technique.

Simple ratios for the determination of inertial parameters, based on the previously discussed dissection work, are presented in Miller and Nelson (1973). As the cadaver population in these studies consists solely of males, the applicability of these ratios for determination of inertial parameters in females is questionable.

Some attempts have been made to develop sex and/or size specific ratios for determining inertial parameters in living subjects. Tichonov (1976) provided tables of values for moments of inertia for the limbs of both male and female sportsmen. Radius of gyration ratio values for the limbs on the basis of level of qualification of the athlete, were similarly provided. The values were determined using a technique similar to the torsional pendulum method.

Widule (1976) using the data from Dempster (1955), developed an equation to allow the determination of segmental moments of inertia for any individual in proportion to their height and weight. No experimental validation was provided for the scaled values.

Katch and Gold (1976) developed normative data for body segment weights, volumes and densities by gathering all available data in the area. They felt that in lieu of having population specific values, normative data would make application more reliable.

The procedure of applying cadaver data to data determined directly from living subjects provides a means for developing much needed anatomical data. Johnson (1976) provided tables for the determination of the location of the center of gravity for all segments for both male and female subjects. These locations were determined experimentally on 20 living subjects. Similarly the per cent ratio of segment weight to whole body weight means were given. Immersion techniques were used to calculate volumes and mass was determined by assuming a mean weight density of each segment.

Kjelosen (1972) provided ratios for segment weights, limb lengths and locations of the center of gravity of the trunk. Dempsters (1955) cadaver data were applied to water displacement data gathered on 12 college women of different body types. The trunk center of gravity location for the two select groups were determined using a cardboard cutout model fitted with a strip of lead. The mass distribution of the lead strip was determined using the proportions dictated by Dempster (1955). (Kjeldsen,1972).

Plagenhoef et al.(1983), using the same techniques as Kjeldsen (1972), similarly provided per cent ratios for segmental weights, segment lengths and center of gravity location of the trunk. Data was obtained on 100 female subjects. No attempt was made to classify the subjects in terms of body build. In addition to the aforementioned parameters, Plagenhoef et al. (1983) determined segmental center of gravity and radius of gyration ratios as well as radii of gyration per cent location of the trunk. Segmental center of gravity locations were determined by submerging the segments to the locations outlined by Clauser et al. (1969). The radius of gyration locations of the extremities, obtained from Dempster's (1955) data, were corrected relative to the center of gravity determined for the living. A lead model was constructed and used to determine the radius of gyration for the trunk segment using the period of oscillation formula.

The aforementioned methods of obtaining body segment parameters on living subjects have many inherent limitations. Computational procedures may not be suitable for populations other than those from which the cadaver data was drawn. Immersion, quick release and reaction change methods are more suitable for the determination of parameters for extremities than for the trunk and head. With the exception of the computerized tomography method, no technique has the ability to determine the three principal moments of inertia. Computerized tomography is perhaps the most promising technique for the future, however it requires very expensive and sophisticated equipment which may not be readily available to most biomechanics researchers. Finally, as was pointed out by Miller and Nelson (1973), it may not be administratively feasible to calculate body segment parameters for each individual segment for every subject, when performing a kinetic analysis on a large number of subjects.

Mathematical Models

The final classification for the estimation of human segmental parameters is that of mathematical models. The increased widespread use and availability of computers has made it possible to carry out extensive calculations of body segment parameters quickly and accurately and has encouraged the development of mathematical models of the body (Miller and Nelson,1973). The human body is modelled as a system of N rigid segments connected to each other by joints (Jensen,1976). According to Clauser et al.(1969), the common element shared by all models is their attempt to represent the irregular shapes of the different body segments with geometric forms which are capable of simple mathematical descriptions.

Generally speaking, there exists two basic approaches to modelling the human body. The anthropometric or geometric method is based on the assumption that each segment may be represented by a single, simple geometric solid of revolution. The partial anthropometric, or segment-zone, approach, although fundamentally the same as the anthropometric model, is based on the notion that each segment should be represented by a number of simple geometric solids. This approach has the advantage of taking into account shape fluctuations which occur along the segment. The basic principle underlying this method is that the sum of the parts will equal the whole (Katch et al.,1974).

In addition to these two basic approaches, there exists two available techniques for obtaining the dimensions which define the parameters of the chosen model. The direct approach, simply stated, involves obtaining size parameters directly from the subject. The alternative to this is the photogrammetric technique, in which the necessary measurements are taken from a photograph of the subject. The advantage of photogrammetry is that subject-researcher interaction time is minimal. On the other hand, taking direct measurements prevents the introduction of errors to which photo-image techniques are subjected (Hatze,1980).

Hence, four fundamentally distinct types of models exist, each defined as a combination of two of the aforementioned distinguishing features.

Hanavan's (1964) 15-segment mathematical model of the human body, although not the first to be developed, is the most widely cited in the literature. Each segment was represented with a single, simple geometric solid. The 25 anthropometric dimensions required as input parameters for this computerized model, were obtained directly from individual subjects. Barter's (1957) regression equations were used to define the weight distribution of the segments. Validation testing of the model indicated prediction of within 10 per cent of criterion segmental center of gravity locations and specific gravity values. Similarly, the center of gravity of the whole body was predicted within seven tenths of an inch and the principal moments of inertia were predicted within 10 per cent error of the criterion. The experimentally determined criteria were those reported by Santschi et al (1963) and Dempster (1955).

Hall and Depauw (1982) utilized a photogrammetric anthropometric model to predict total body mass centroid location. The model was an 18-link version of the human body. Each segment link was represented by one of four selected geometric solids. Validation testing of the model was conducted with a group of 40 male and female subjects ranging in age from 6-35 years. The criterion center of gravity location was determined using the reaction board technique. The average error in using the model to determine the center of gravity location was found to be 1.6 per cent. The authors concluded that while the present investigation involved only total body mass centroid analysis, the model could be extended for prediction of other inertial parameters (Hall and Depauw, 1982).

Several authors report using the partial anthropometric approach coupled with direct measurement techniques, for modelling the human body. Katch et al. (1974,1975) proposed such a method for estimating segmental and total body volumes for both men and women. They divided the body into seven generalized segments, each of which was subdivided into several zones. Twenty-six anthropometric measurements were required to calculate volumes. Validity coefficients for criterion (immersion) versus calculated volumes were computed and all were found to be significant at less than the .01 level except for the feet.

A modified version of Katch's (1974,1975) segment zone model was proposed and tested for its accuracy in determining total body volumes first on male subjects of different sizes (Sady et al.,1978), and later on female subjects (Freedson et al.,1979). In view of the high validity coefficients obtained, it was concluded that the summation of the segmental geometric shapes for calculating volume closely approximated the actual body volume. The model was found to be neither size specific (Sady et al.,1978), nor sex specific (Freedson et al.,1979).

Hatze (1980) presented a method for determining parameter values of segments using the partial anthropometric-direct measurement approach to modelling. This model was the most extensive and theoretically complex mathematical model surveyed by the author. The model consists of 17 segments, each subdivided into small mass elements of different geometrical structures. No assumptions of uniform density were made, hence each mass element was assigned its own density value. A special subcutaneous fat indicator further allowed the adjustments to densities of some segmental elements on the basis of their predictable fat content. No assumptions of symmetry were made, and the model took into account all changes in body morphology as well as differentiated between male and female subjects. A battery of 242 direct anthropometric measurements defined the input parameters of the model. Validation was provided by comparing experimentally determined values of volumes, masses, center of gravity locations and principal moments of inertia with model predictions for four different subjects. The overall accuracy of the model was found to be better than 3 per cent.

Jensen's (1976b,1978) photogrammetric, segment-zone method illustrates the final approach available for determining human segmental parameters from mathematical models. This model was based on the elliptical zone assumption which was previously made by Weinbach (1938). Weinbach constructed volume contour maps in order to determine the center of gravity and moments of inertia of the whole body or its segments. The basic assumption was that serial horizontal sections through the body were elliptical in shape. By taking measurements, either directly from the body or from a photograph, at the recommended locations, the area could be calculated for each location by applying the formula of the known geometric shape (ellipsoid). After plotting area versus location from the soles of the feet, the center of gravity and moments of inertia can be determined by taking the first and second moments of that volume contour map.

Validation for this technique was provided by Dempster (1955), who found the accuracy of the volumes to be good with the exception of the shoulders. Similarly, Rodrigue and Gagnon (1981) provided validation for both the Hanavan and the Weinbach models for the estimation of the forearm volume and position of center of mass. Using the forearms of 20 embalmed cadavers, they determined the volume and center of mass for the segments using the Hanavan model (frusta of a cone), the Weinbach model (20 elliptical zones), and compared them to their criterion measures which were determined using axial tomograpy. They concluded that the Weinbach model provided better estimates of the volume and location of the center of mass than the Hanavan model. In all instances, however, the error was less than 7.5 per cent, thus it was concluded that both models were capable of accurately predicting the location of the center of mass and the volume of the forearm. The superiority of the Weinbach model was attributed to the fact that it properly adapted to the shape fluctuations of the forearm (Rodrigue and Gagnon,1981).

The Jensen (1976b) computerized mathematical model, based on the aforementioned elliptical zone assumption, was a 16-segment, photogrammetrically based model of the body.

Similar segments as were defined by Hanavan (1964) were likewise utilized in this model, with the inclusion of the neck as a separate entity. Each body segment was assumed to be composed of a number of elliptical zones of known density. The zones were two centimeters wide, narrower at the ends if necessary. In order to determine mass, Dempsters (1955) density values were used. To compare the results from the model (Zone) with those of Hanavan, Jensen collected, from subjects, the required anthropometric measurements and ran Hanavan's Design program. The Jensen model was ~~used~~ as the criterion as it took into account shape fluctuations of the segments. Similarly, in order to test the validity of the program, a geometric human figure was constructed and the Hanavan model was used as the criterion. The overall accuracy of the Zone program was found to have less than 5 per cent error in determining segmental parameters of the geometric figure. Although no experimental validation was provided, Jensen concluded that the Design program of Hanavans was inadequate especially when considering the moments of inertia of the hands and feet. It was suggested that the Hanavan model need be refined to redesign geometric shapes for these segments.

Similar comparisons and validation were provided by Jensen (1978). Estimated total body masses of young boys were calculated using the Jensen model, the Hanavan model and then compared to those determined on a weigh scale. The per cent error associated with using the Jensen model was 1.38 whereas the Hanavan model underestimated the total body mass with an average error of 9.7 per cent. In a subsequent study, Jensen (1981) compared subjects ranging in age from 4-12 years and found the mean error for predicting body mass was -12.36 per cent for the Hanavan model compared to only 0.68 per cent for the elliptical zone method. It was concluded from these results that the elliptical zone method is more accurate than the Hanavan model when applied to children (Jensen, 1978).

Most of the criticism the anthropometric models of the human body receive is attributable to their lack of conformity to the shape fluctuation of the segments. This problem may be alleviated by using a segmental zone approach to modelling as was done by Jensen (1976b,1978). With specific reference to the Hanavan (1964) model, its applicability is limited as the determination of mass is based on statistical predictive equations. Jensen (1976b,1978), on the other hand, assumed known segmental densities. These densities, however, were still based on cadaver studies and their use may be questionable. With the exception of that proposed by Hatze (1980), all models make the assumption of uniform density. Such an assumption introduces inaccuracies in the region of 4-7 per cent, in the computed values of the principal moments of inertia (Hatze,1980). The Hatze (1980) model takes into account and corrects for all the short comings of previous models. The direct measurement technique was used to collect the battery of 242 anthropometric measures which define the input parameters of the model. Direct measurement techniques prevent the introduction of errors to which photo-image techniques are subjected (Hatze,1980). The photogrammetric technique, on the other hand, is of value in that subject-researcher interaction time is minimal. Indeed, Jensen (1978) reported that less than 10 minutes of the subjects time was required while Hatze (1980) required approximately 80 minutes for the collection of the anthropometric input data for each subject.

Summary

The inertial information obtained through the aforementioned methods is of interest to researchers in fields as diverse as kinesiology, medicine, ergonomics and space technology. There are a number of factors that may dictate which source will be used to obtain the necessary segmental parameter data. Ultimately, the decision is that of the researcher. Darnis (1980) outlined the three sources that are available. Direct measurements such as immersion and reaction change, although potentially the most accurate, are difficult to carry out, time consuming and the results tend to depend on the method utilized. Computational procedures, such as Barter's regression equations, allow the estimation of any individuals segmental parameters. Mathematical models allow rapid calculation of inertial parameters from anthropometric data. Dainis (1980) cautioned that when the data bases for the last two techniques depend upon the rather small sample of cadavers, they cannot be used with confidence on members of different populations.

The problem of applicability of these existing sets of data must be addressed. To make the data more widely applicable, the sample of cadaver data need be extended to include segmental density values, and other inertial parameters, for women, children and athletes. In lieu of having these population specific values, and provided the inherent limitations are recognized, the continued use of existing sets of cadaver data is warranted. Indeed, several researchers have used this data to collect and/or generate body segment parameter values on members of sub populations (Kjeldsen,1972; Jensen,1976; Plagenhoef,1983). Such procedures are warranted, as is the continued use of those body segment parameter values generated from them, until such a time when more suitable alternatives become available.

Justification

The need for body segment parameter data was evidenced by the abundance of literature published in the area. The application of existing sets of data has been made by researchers from many different and diverse fields of study. The problem of applicability of such data to the female population, for example, has been a complex one.

Harless (1860) determined that age and sex were significant factors in explaining the distribution of values of the specific gravity of the body segments. Yet still today, the specific gravity values most frequently used when determining the inertial parameters of young females body segments are those presented by Dempster (1955). Such an occurance has been dictated by current knowledge, as no specific gravity values have been obtained from a sample of female cadavers. The absence of female data reflects the overall paucity of cadaver dissection work done for the purpose of body segment parameter determination. The obvious solution to this problem would be to extend the sample of cadavers studied to include a representative sample of females from the population. Unfortunately obvious solutions are not always practical, as evidenced by the reluctance of researchers to undertake such an investigation.

Unfortunately the question of applicability of cadaver data to female subjects extends beyond the specific gravity problem. Research in the area has revealed the existence of sexual dimorphism in body segment volumes and shapes (Freedson et al.,1979). It stands to reason that sex differences in mass distribution values, both between and within segments, as well as their center of gravity locations would have also exist. Indeed, several researchers have discovered sex differences in segmental weight and/or mass distribution, between segment, ratios (Kjeldsen,1972; Johnson,1976). Simliarly, the center of gravity locations of some segments have been found to vary between male and female subjects (Kjeldsen,1972; Johnson,1976; Hall and Depauw,1982). No known comparisons have been made between the segmental moment of inertia locations for different sexed subjects.

Body segment parameter proportionality values have likewise been shown to be influenced by body size, thus further complexing the problem of applicability. Again, the problem exists because no cadaver segment parameter values for varying body types exist. Although Dempster's (1955) cadaver sample did not adequately represent the wide range of body types in the population, ratio values determined on living subjects of 4 different body builds were presented. These results indicated that body type affected segment volume distribution. In light of these findings, Dempster and Gaughran (1967) concluded that much additional information was needed to determine the relationship which exists between body physique and the distribution of mass and the center of mass. Similarly, Drillis et al (1964) expressed their concern for the need to develop relationships between body parameters and body build. Indeed, after further investigation, they published results which indicated the dependence of various segment volume values, expressed as a percentage of total body volume, on the body physique of the subjects (Drillis et al.,1966). Jensen (1978) collected and compared the body segment parameter values from prepubescent boys of markedly different somatotypes. Comparisons were made between the endomorph and ectomorph , and between the endomorph and mesomorph in terms of distribution of masses and principal moments of inertia. The greatest differences in inertial parameters existed between the ectomorph and endomorph. Kjeldsen (1972) compared center of gravity locations of the segmented trunk, segment lengths and segment weights between two selected groups of females : those whose hip width exceeded shoulder width and those whose shoulder width exceeded hip width. Several significant differences were found to exist between the groups. Generally speaking, Kjeldsen (1972) concluded that in movement analysis dealing with the trunk-segments and /or the lower limbs, the body build of the female would have to be taken into consideration.

In light of these findings, one would hope to be able to find size and inertial parameter values for college-age females of different body types. In actual fact, however, the work of Kjeldsen (1972) was the only one in the literature to present values on selected segmental parameters for women of different body types. Unfortunately, the method uttilized to classify subjects failed to fully account for the wide variety of body physiques found in the normal population. Also, as no values were presented for segmental center of gravity or moment of inertia locations, a complete kinetic analysis could not be performed using only this data set. Plagenhoef et al (1983) , although disregarding body build of their subjects, provided the only complete set of anatomical data for college-age female subjects. Complete, in the sense that it allowed the estimation of the size and inertial parameters necessary for the analysis of human motion (neglecting soft tissue motion and motion of the extremities about their long axis) (Plagenhoef et al, 1983).

It was the author's contention that the need existed for the establishment and generation of a complete set of body segment parameter data for college-age females of different and distict body types, as determined by means of somatotyping. In order for the purposes of this investigation to be fulfilled, one of the three classifications for the estimation of segmental parameters had to be selected and used. For reasons previously discussed, the cadaver study alternative was eliminated. To collect those parameters required to provide a complete anatomical data set using empirical techniques with living subjects would necessitate a phenominal amount of time and energy on the part of the researcher. Other reasons for eliminating this classification as the technique of preference were previously discussed in the review of literature. Hence the mathematical modelling method was utilized in this study. The decision to use this method, although made partially by the process of elimination, was supported by several advantages. Mathematical modelling was the only method, with the exception of axial tomography, which allowed the estimation of the moments of inertia about each of the three principal axes from living subjects. Perhaps the availability of moment of inertia values about the long axis of the body segments would allow and encourage more accurate analyses of three dimensional motions.

The Jensen (1976b, 1978) mathematical model was selected for use in this study. This model had the advantage of being photogrammetrically based, hence, subject-researcher interaction time would be minimal. The other key advantage lay with the model's ability to account for shape fluctuations along each segment. The accuracy of the model has been established as being good for estimating total body mass (Jensen,1976,1981a,in press), and total body moments of inertia (Jensen,1981b).

Chapter III

METHODOLOGY

The purpose of this study was to establish and generate a complete set of body segment parameter data for college age women of different body types. A photogrammetric mathematical model was utilized to determine the size and inertial parameters of interest.

Subject Selection

Fifteen female, college-age subjects were used in this study. All subjects were either graduate or undergraduate students in the Faculty of Human Kinetics at the University of Windsor. Initial subject selection occured following a subjective evaluation of available body types in the population. An attempt was made to select and categorize those subjects that represented relatively distinctive body types. Verification and further classification of subjects was made using the Heath-Carter (1967) somatotype method. The predominance of one component in the rating scale served as an adequate criterion for classifying subjects as either endomorphic, mesomorphic or ectomorphic. This selection process resulted in unbalanced group size, specifically, five endomorphs, four mesomorphs and six ectomorphs.

Preparation of Subjects

Selected subjects were informed of the testing procedures and asked to sign a consent form (Appendix A). The testing process included a somatotyping session and a photography session. Subject-researcher interaction time for these test procedures was aproximately 40 minutes.

Somatotype Determination

Subjects were asked to wear indoor gym clothes to the first test session. The measurements required for the determination of the Heath-Carter somatotype rating were obtained by a trained anthropometrist. The mean of three measures obtained for each of height, weight, skinfolds (triceps, subscapular, suprailiac, calf), bone diameters (humerus, femur) and muscle girths (flexed arm, calf) were calculated and recorded on the somatotype rating form (Figure 1). Details of the instruments and techniques that were used to obtain these measures may be found elsewhere (Ross & Marfell-Jones, 1982). Similarly, the detailed procedures used in obtaining the somatotype ratings from the

HEATH-CARTER SOMATOTYPE RATING FORM

NAME J.B. AGE 45-2 SEX: M F NO: 135

OCCUPATION Teacher ETHNIC GROUP Caucasian DATE 11 Nov 1966

PROJECT: A.T.P. MEASURED BY: L.C.

Skinfolds (mm):

Triceps = 13.0

Subscapular = 15.3

Supraliac = 9.9

TOTAL SKINFOLDS = 38.2

Calf = 9.8

TOTAL SKINFOLDS (mm)

Upper Limit	10.9	14.9	18.9	22.9	26.9	31.2	35.8	40.7	46.2	52.2	58.7	65.7	73.2	81.2	89.7	98.9	108.9	119.7	131.2	143.7	157.2	171.9	187.9	204.0
Mid-point	9.0	13.0	17.0	21.0	25.0	29.0	33.5	38.0	43.5	49.0	55.5	62.0	69.5	77.0	85.5	94.0	104.0	114.0	125.5	137.0	150.5	164.0	180.0	196.0
Lower Limit	7.0	11.0	15.0	19.0	23.0	27.0	31.3	35.9	40.8	46.3	52.3	58.8	65.8	73.3	81.3	89.8	99.0	109.0	119.9	131.3	143.8	157.3	172.0	188.0
FIRST COMPONENT	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12

Height (in.) = 67.1

Bone: Humerus (cm) = 6.82

Femur = 9.27

Muscle: Biceps 33.0 − 1.3 (cm) = 31.7

− (triceps skinfold)

Calf 35.1 = 34.1

− (calf skinfold) .98

55.0	56.5	58.0	59.5	61.0	62.5	64.0	65.5	67.0	68.5	70.0	71.5	73.0	74.5	76.0	77.5	79.0	80.5	82.0	83.5	85.0	86.5	88.0	89.5
5.19	5.34	5.49	5.64	5.78	5.93	6.07	6.22	6.37	6.51	6.65	6.80	6.95	7.09	7.24	7.38	7.53	7.67	7.82	7.97	8.11	8.25	8.40	8.55
7.41	7.62	7.83	8.04	8.24	8.45	8.66	8.87	9.08	9.28	9.49	9.70	9.91	10.12	10.33	10.53	10.74	10.95	11.16	11.37	11.58	11.79	12.00	12.21
23.7	24.4	25.0	25.7	26.3	27.0	27.7	28.3	29.0	29.7	30.3	31.0	31.6	32.2	33.0	33.6	34.3	35.0	35.6	36.3	37.1	37.8	38.5	39.3
27.7	28.5	29.3	30.1	30.8	31.6	32.4	33.2	33.9	34.7	35.5	36.3	37.1	37.8	38.6	39.4	40.2	41.0	41.8	42.6	43.4	44.2	45.0	45.8

SECOND COMPONENT	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9

Weight (lb.) = 147.0

$Ht./\sqrt[3]{Wt.}$ = 12.76

Upper limit	11.99	12.32	12.53	12.74	12.95	13.15	13.36	13.56	13.77	13.98	14.19	14.39	14.59	14.80	15.01	15.22	15.42	15.63
Mid-point	and	12.16	12.43	12.64	12.85	13.05	13.26	13.46	13.67	13.88	14.09	14.29	14.50	14.70	14.91	15.12	15.33	15.53
Lower limit	below	12.00	12.33	12.54	12.75	12.96	13.16	13.37	13.56	13.78	13.99	14.20	14.40	14.60	14.81	15.02	15.23	15.43
THIRD COMPONENT	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9

	FIRST COMPONENT	SECOND COMPONENT	THIRD COMPONENT	
Anthropometric Somatotype	4	5	2½	BY: L.C.
Anthropometric plus Photoscopic Somatotype				RATER:

Figure 1. Somatotype Rating Form (figure from Heath-Carter, 1967)

information contained on the rating form are published elsewhere (Heath-Carter, 1967).

Segment Delineation

Subjects were required to wear a bathing suit and cap to the photography session. Joint centers and segment boundaries were marked primarily with a black skin pencil. White tape was used to delineate the upper/lower trunk and trunk/thigh boundaries. The methods used to delineate the segments were similar to those established by Dempster (1955) and used by Clauser (1969), Kjeldsen (1972) and Plagenhoef (1971). The modifications incorporated by Jensen (in press) were also used. The planes of separation were established using bony landmarks as reference points. In most instances, these planes corresponded with the saw cuts used by Clauser (1969).

The wrist separation plane began at the palpable groove between the lunate and capitate bones, crossed over the mid point of the pisiform bone and ended at the distal wrist crease (Appendix B). The demarcation line separating the hand and forearm at the elbow went from the area of insertion of the triceps on the olecranon process, across the greatest projection of the medial epicondyle of the humerus and ended at the skin crease on the anterior surface (Appendix B). The shoulder plane of separation began at the articular facet of the clavicle and ran anteriorly and posteriorly to the axilla, following the medial border of the deltoid muscle (Appendix B). The mass surrounding the head of the humerus and acromium process was included as part of the upper arm. The ankle separation plane began at the anterior, superior edge of the head of talus and passed through the superior border of the calcaneous, anterior to the Achilles tendon as palpated medially (Appendix B). The demarcation line at the knee began at the lower third of the patella and extended through the maximum protusions of the medial and lateral epicondyles of the femur (Appendix B). The hip separation plane extended from the crest of the ilium, anteriorly over the anterior superior spine of the ilium and posteriorly over a site just above the femoral trochantor, toward the ishial tuberosity (Appendix B). The upper and lower trunk was segmented by taking a transverse section at the level of the inferior edge of the xiphoid process of the sternum. The neck and upper trunk were divided posteriorly between the seventh cervical and first thoracic vertebrae and anteriorly along the upper border of the first rib. The head and neck were segmented by taking a transverse section passing through the body of the second cervical vertebrae. Figure 2 illustrates the planes of separation for all of the segments as were established using the aforementioned body landmarks.

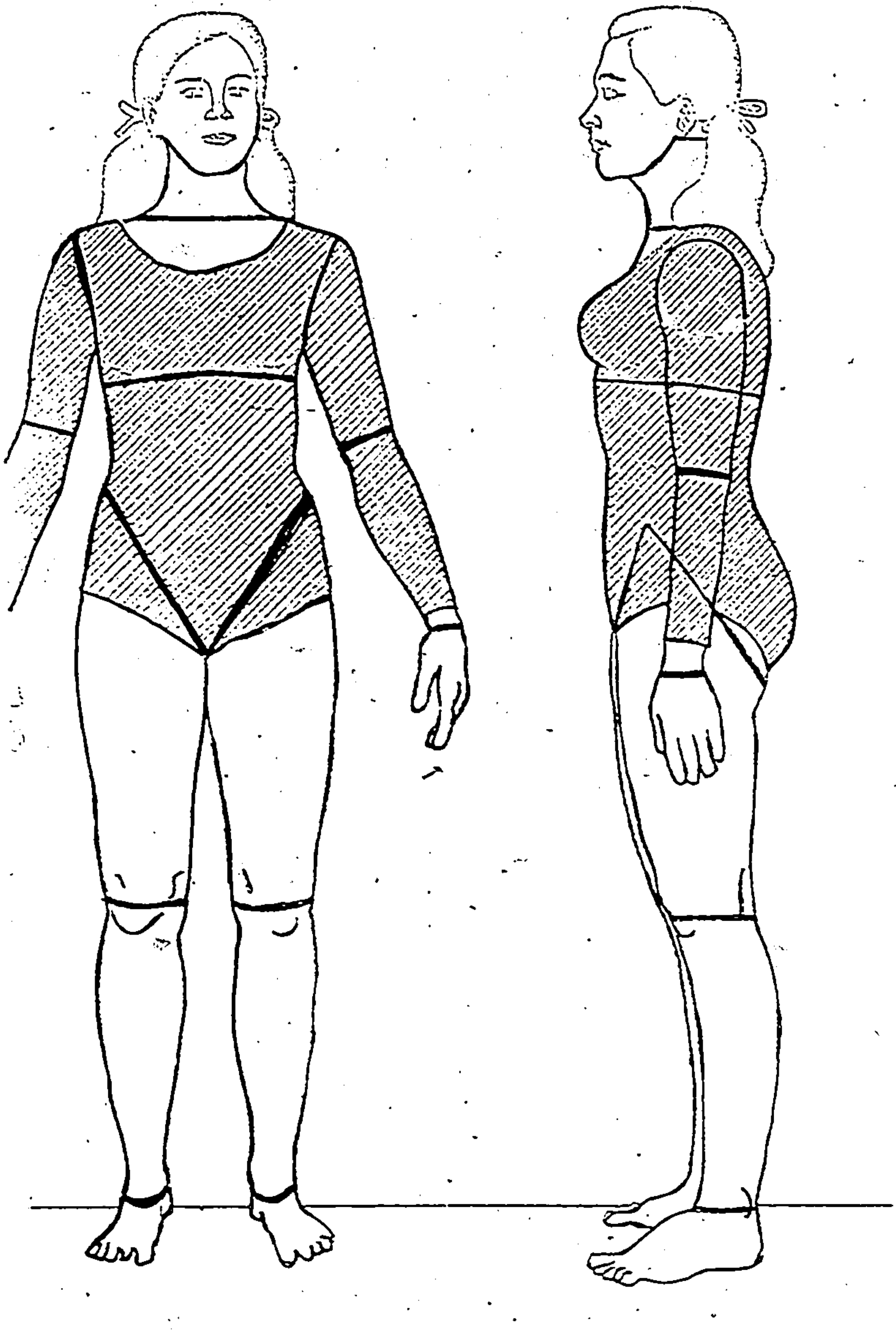

Figure 2. The Planes of Separation (figure from Kjeldsen, 1972)

Positioning Procedures

The procedures that were utilized for placing the marked subject in the reference position were similar to those outlined by Jensen (1978,in press). One modification that was incorporated for the purposes of this study was that the subjects were photographed in an erect position. It was felt that the supine position assumed by the subjects in the Jensen studies, (1976,1978,1981ab,in press), may have caused significant distortion of the configuration of the posterior side of the body. Hence the erect position was assumed in an attempt to alleviate this potential source of error. In order to increase the number of zones of the foot, the recommended plantar flexed position was resembled as closely as possible. Hence, the subject was required to stand on an incline board angled at 30 degrees. To ensure that the outline of all of the segments could be seen, the neck was hyperextended, the arms were positioned at the sides so that both the anterior and posterior contours of the trunk were visable, the palms were faced down and the fingers extended. As much as possible, the segment links were arranged so that they were parallel to the Z axis.

Photography Procedures

Two 35mm cameras, each fitted with a 50mm lens, were used to obtain the photographic records of the marked subjects in the reference position. One camera was located 4 meters from the mid-sagittal plane, the other at an equal distance from the frontal plane. Both cameras were positioned on tripods and were loaded with Kodak black and white, 400 ASA, indoor film. Horizontal and vertical references were placed in the field of view, behind the subject. These axes served as the reference axes for both the X-Z and Y-Z planes.

Data Collection

A computerized mathematical model, previously proposed by Jensen (1976,1978) was used to determine the size and inertial parameters of interest. Each segment of this 16-segment model was assumed to be composed of N serial, horizontal elliptical zones, two centimeters wide. Hence the required input parameters were obtained by digitizing the endpoints of the N+1 sections from the photographic records of each subject. A Numonics electronic graphics calculator was used for these purposes.

Digitizing Procedures

The two photographs, (X-Z,Y-Z), per subject were fixed on a table so that the reference axes were aligned with the X-Y cartesian co-ordinate system of the digitizer.

Similarly, the location of the apex of the head in both photographs was aligned with respect to the X co-ordinate.

The input parameters which defined the model required that two pairs of y co-ordinate endpoints be recorded for every two centimeter increment of the x co-ordinate. The The measured height of the subject was used to set the scale in the field of view. The Y co-ordinates corresponding with every 2 cm increment yielded the major and minor axes and were namely, front/back endpoints (X-Z plane) and left/right endpoints (Y-Z plane). The axes of adjacent sections formed the elliptical zones (Figure 3). Similarly, the proximal and distal joint centers were digitized and the X,Y,Z coordinates determined for both centers. The two planar views of the sectioned body, with joint centers marked, are illustrated in Figure 4.

Each of the 10 segments were digitized in this manner, however the occurance of significant perspective error in the photo images necessitated the calculation of different conversion constants for each digitized segment.

Data Reduction

The Jensen Model

The obtained digitized values served as the input parameters for the computerized model written in Fortran IV

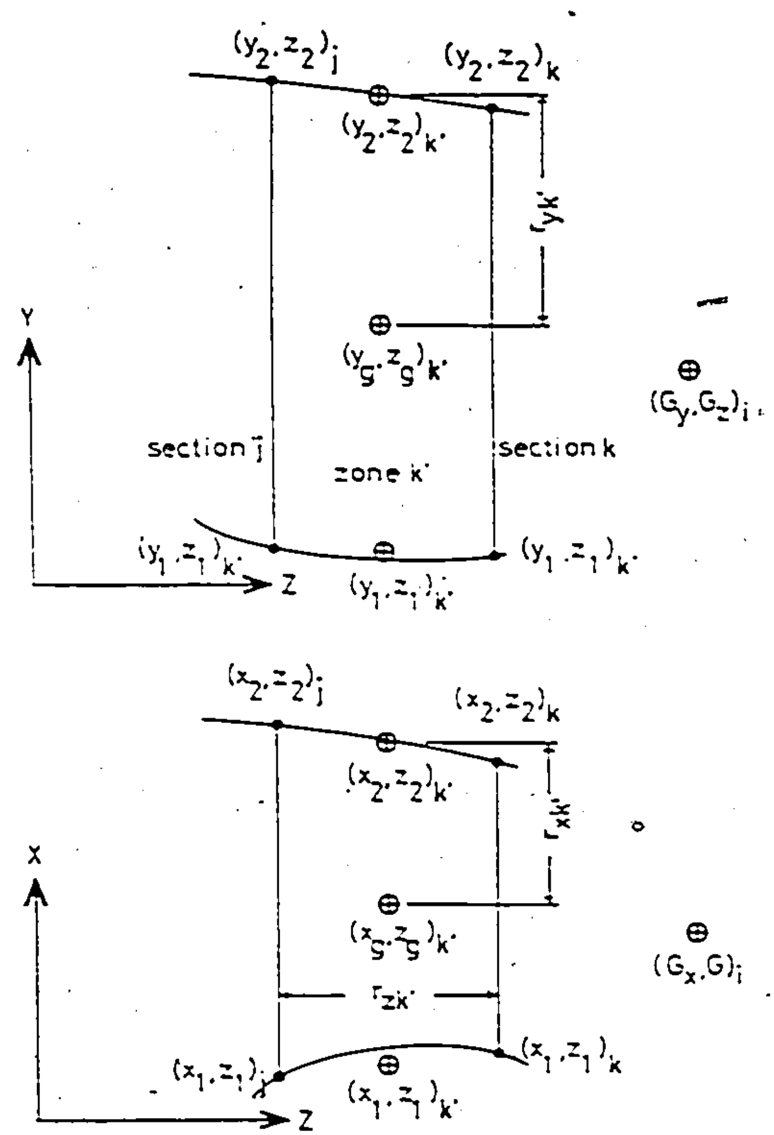

Figure 3. Diagram of a Sectioned Zone
(figure from Jensen, 1976b)

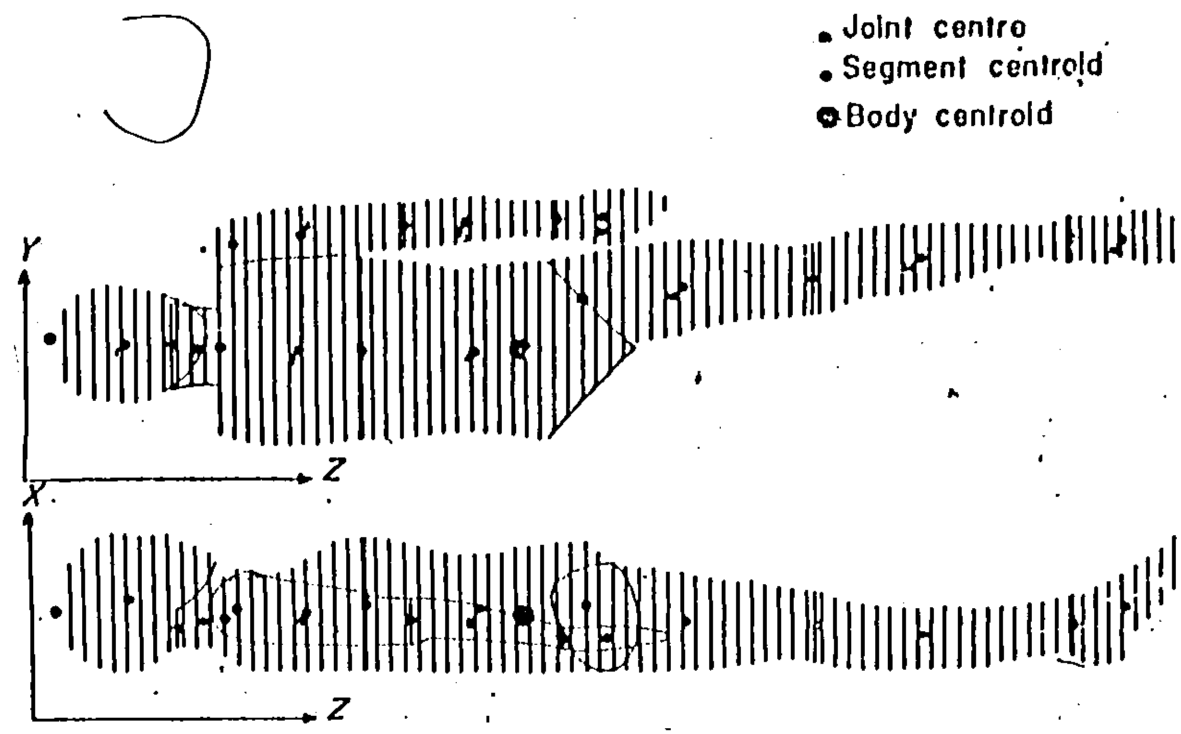

Figure 4. The Sectioned Body (figure from Jensen, 1978)

(Jensen, 1964). The segment lengths were determined from the digitized coordinates of the proximal and distal joint centers. Subsequently, the program determined the radii, thickness and the centroid about each axis for each zone. The volume, first moments of volume and the moments of inertia about the centroidal axes for each zone were determined by applying standard formula for elliptical plates. By summing across zones, segment volumes were determined. The assumption of known density was made in order to determine the inertial parameters of the body segments. Clauser's (1969) segment density values were previously incorporated into the program for this purpose. As Clauser (1969) did not provide different values for upper and lower trunk, a proportional split of trunk density based on the work of Dempster (1955) was used. The segment density values utilized are listed in Table 1. Using these values, segment mass, first moments of mass, and subsequently segment mass centroid locations were determined. The mass moment of inertia of each zone about its centroidal axes was found and by applying the parallel axis theorem and summing across the zones, the mass moments of inertia of each segment were determined. By assuming that the body axes were principal axes, the calculated mass moments of inertia of the segment about the centroidal axes were the principal moments of inertia. Specific details of

Table 1

Segment Density Values*

Segment	Density($kg\text{-}m^{2}$)
Head	1070
Neck	1070
Upper Trunk	920+
Lower Trunk	1010+
Upper Arm	1060
Forearm	1100
Hand	1110
Thigh	1040
Calf	1080
Foot	1080

* from Clauser, C.E. et al (1969)
+ proportional split based on Dempster (1955)

the mathematical model are published elsewhere (Jensen, 1976a,1978).

Data Analysis

Dependant Variables

The size and inertial parameters obtained from the computerized model included segment lengths, segmental masses, locations of segmental centers of gravity and radii of gyration and the values for each of the three principal moments of inertia in the reference configuration. The body segment parameter data for the three different groups was presented in percent ratio form. Segment lengths were expressed as a percentage of total body height, segment masses were expressed as a percentage of total body mass and the segmental center of gravity locations, from the proximal joint centers along the long axes, were expressed as a percentage of the segment length. By applying the parallel axis theorem to the values for the three principal moments of inertia through the segment centroids, values for moments of inertia were determined about the proximal and distal joint centers. Subsequently, the radius of gyration values were determined and expressed as a percentage of segment length.

Accuracy of the Model

The accuracy of the mathematical model for determining total body mass of females was established by comparing measured total mass with the computed mass. The per cent error was expressed for each group. This method of evaluating the accuracy of the model has been used by Jensen (1978) and Hatze (1980).

To provide a further measure of the accuracy of the model, selected parameter values were compared with those available in the literature. Included were values for segmental length and weight ratios (Kjeldsen,1972; Plagenhoef,1983) and segmental mass centroid locations expressed as a percentage of segment length (Hatze,1980; Plagenhoef,1983; Hall and Depauw,1982). Similarly reported in the literature were proximal and distal radius of gyration values expressed as a percentage of segment length (Plagenhoef,1983) and a value for the moment of inertia about the λ axis through the mass centroid (Hatze,1980). The method of comparing determined values with those reported in the literature has been used previously (Kjeldsen,1972; Hatze,1980; Hall and Depauw,1982), and was the method of choice in lieu of having experimentally determined parameters available. Essentially this method provided a means to validate data by checking whether the computed values fell within a range defined by those pre-established norms. Where obvious differences occured, further examination of the data, taking into consideration the height and weight characteristics of the subjects, ensued. Where possible, differences were attributed to differences in body morphologies.

Statistical Procedures

To establish if significant differences existed between the groups, thus warranting the generation of three different sets of data, values between groups were tested for statistical significance. A one-way analysis of variance was utilized for every dependant variable. Each of the variables (segment mass, segment lengths, center of gravity locations, radius of gyration about each principal axis through both proximal and distal joint centers), were tested in their ratio forms. Scheffe's post-hoc multiple comparisons test was employed where significant F-ratios were found. The significance level adopted for all levels was $p < .05$.

Chapter IV

RESULTS AND DISCUSSION

The purpose of this study was to predict the body segment parameters of college age women of three different body types. In so doing, the accuracy with which the chosen mathematical model predicted the inertial parameters of females was established. Subsequent statistical analyses were performed for each of the model predicted parameters to determine if, and where, significant differences existed between the three group means.

Fifteen college age women served as subjects in this study. Each was classified, in accordance with the Heath-Carter (1967) method of somatotyping, as being either endomorphic, mesomorphic or ectomorphic. The group assignment, age, height, mass and somatotype rating of each subject is presented in Table 2. Extreme mesomorphic body types were not available in the population from which the sample was drawn. Hence, the mesomorphic group tended to be representive of the "normal" female body type (neither extremely fat, thin, nor muscular).

Table 2

Physical Characteristics of Subjects

Group	Age (yrs)	Height (cm)	Mass (kg)	Somatotype
Endomorphs (n=5)	20	166.80	68.60	9-6-.5
	20	170.00	83.70	8-6-.5
	21	170.00	87.50	9.5-4.5-.5
	29	167.70	82.20	9-6.5-.5
	21	161.50	87.90	8.5-7.5-.5
Mesomorphs (n=4)	22	153.80	47.20	3-4-2.5
	22	163.50	61.00	3-4.5-2
	22	166.40	60.10	3.5-4.5-2.5
	21	163.50	59.10	4-4-2
Ectomorphs (n=6)	22	167.50	52.30	3-3-4.5
	23	165.00	52.00	3-2.5-3.5
	22	174.30	56.90	3.5-1-4.5
	20	172.50	54.70	3-2-5
	22	162.00	45.40	1.5-2.5-3.5
	25	179.30	58.10	3-1.5-5.5

Accuracy of the Model

The accuracy of the mathematical model for determining the total body mass of females was established by comparing measured total mass with the model computed mass (Table 3). Similarly presented in Table 3 are the discrepancies between the actual and estimated masses, expressed as per cent error. The absolute mean per cent error for the total sample was found to be .77% with a standard deviation of ±.42%. Hence the overall accuracy of the model for determining total body mass of females was better than 99%. These values are comparable to those reported in the literature. Miller and Morrison (1975), using an updated version of the Hanavan model, found overestimates of total body weight by an average value of 4.59 ±1.98%. Jensen (1978) reported the estimation error for total body mass to be less than 2% for the three subjects studied. Hatze (1980) found the mean of the absolute values of the relative errors for the four subjects studied to be .26%. Similarly reported values from subsequent studies include .61% mean error with a standard deviation of 2.18% (Jensen,1981a), .203% mean error with a standard deviation of 2.301% (Jensen,in press) and 1.14% mean error (Yokoi et al,1985).

Miller and Morrison (1975) reported that the greater the subjects weight, the less the tendency that the sum of

Table 3

Accuracy of Body Mass Estimates

Group	Mass (kg)	Estimated Mass (kg)	Accuracy (%)	Error (%)
Endomorphs	88.60	87.77	99.06	0.94
	83.70	83.70	100.00	0.00
	87.50	88.28	99.11	0.89
	82.20	81.97	99.72	0.28
	87.90	88.41	99.42	0.58
Mean=			99.46	0.54
SD=				.40
Mesomorphs	47.20	46.70	98.94	1.06
	61.00	60.13	98.58	1.42
	60.10	59.91	99.68	0.32
	59.10	59.95	98.57	1.43
Mean=			98.94	1.06
SD=				.52
Ectomorphs	52.30	51.99	99.40	0.60
	52.00	51.49	99.03	0.97
	56.90	57.09	99.66	0.34
	54.70	54.37	99.39	0.61
	45.40	44.91	98.93	1.07
	58.10	58.69	98.99	1.01
Mean=			99.23	0.77
SD=				.29

the parts would overestimate the whole. No consistency of this nature was evident in the results from this, or the other cited studies.

Taking into consideration the accuracy with which the Jensen mathematical model predicted the total body masses in this investigation, and the consistency of these results with those of similar studies, the model was deemed suitable for use with female subjects.

Segment Masses

The mean values for the model predicted segmental masses, expressed as percentages of total body mass, are presented in Table 4. Also included in Table 4 are segment mass percentage values reported by other investigators. No experimentally determined values were available hence comparison with pre-established norms served as the method of choice to validate the newly generated set of data.

The segment boundaries which defined the head, upper trunk, arm, forearm, hand, shank and foot were similarly established by all reported investigators (Table 4) thus their mass values were comparable. In all instances, the model predicted mass proportions of the aforementioned segments were within .52% of at least one of the other reported means. The greatest observed differences occured

Table 4

Ratio of Segment Masses to Total Body Mass

	Model Prediction		Kjeldsen (a)	Plagenhoef (b)
Segment	Mean	SD	Mean(c)	Mean
Head	6.30%	1.35%	8.42%(d)	8.40%(d)
Neck	2.60	0.76		
Upper trunk	17.54	1.57	15.60	17.02
Lower trunk	21.38	2.12	32.54(e)	28.20(e)
Arm	2.64	0.25	2.82	2.90
Forearm	1.61	0.20	1.53	1.57
Hand	0.60	0.14	0.51	0.50
Thigh	14.63	1.02	10.21	11.75
Shank	5.10	0.49	5.50	5.35
Foot	1.26	0.22	1.30	1.33

a. Kjeldsen,K. (1972)
b. Plagenhoef,S. (1983)
c. Mean value of gymnasts and non-gymnasts
d. includes the mass of the neck
e. sum of abdomen and pelvis values

between the reported values for the head/neck, upper trunk and shank segments. Possible reasons for these discrepancies include the different collection techniques utilized (modelling versus immersion), the different density values employed to determine segment mass (Clauser's versus Dempster's) and/or the variability between the subject populations studied. The disparity between the mean values collected using identical techniques, (Kjeldsen versus Plagenhoef), was as evident as that between the mean values collected using different techniques (Model versus Kjeldsen; model versus Plagenhoef). In certain instances, the chosen density values served to magnify the differences between the presented means. For example, the shank difference of .25% between the mean mass values of 5.1% and 5.35% reduced to a difference of .19% between the predicted volume means after negating the effect of the density values. The opposite effect was also evident for certain segments hence differences produced in one direction tended to average out those in the other direction. The observed differences in segment mass values were probably reflective of the variability between the subject populations studied. Unfortunately neither Plagenhoef nor Kjeldsen reported the height, weight or somatotype characteristics of their sample thus no comparisons on these bases could be made.

The large discrepancies between the cited values for the lower trunk and thigh masses were attributed to the different segment boundaries employed. Both Kjeldsen and Plagenhoef delineated the segments inferiorly (both anteriorly and posteriorly) from the anterior superior spine of the ilium. The plane of separation used in this study, on the other hand, extended inferiorly from the level of the iliac crest thus substantially increasing the mass of the thigh segment while simultaneously decreasing the mass of the lower trunk. The disparity between the means of the combined lower trunk and thigh masses reduced to less than 4%, which again was explained, a priori, as being reflective of the variability between the subject populations.

Comparisons on the basis of height and weight characteristics were made between the mass proportion values presented in this study and those presented by Hatze (1980) and Zatsiorsky and Seluyanov (1981). Using the gamma scanner method, Zatsiorsky and Seluyanov (1981) determined the mass and inertial parameters of the body segments of 100 men. The pertinent anthropometric characteristics recorded for the subjects were mean values for age (23.8 years), height (174.1 cm) and weight (73 kg). Hatze (1980), using a highly sophisticated mathematical model, predicted the segment inertial parameters of 4 subjects, including one 31 year old female (weight=64.63 kg, height-not reported). The females utilized in this present investigation were lighter

($\bar{X}$=65.11 kg) and shorter ($\bar{X}$=166.9 cm) than Zatsiorsky and Seluyanov's sample of men, and slightly heavier than the female subject studied by Hatze. Comparisons between the three segment mass percentage values were possible because of congruent methods of establishing segmental boundaries. Thus the lower trunk and thigh segment values were of particular interest as the newly generated values had not been comparable with those values reported by Kjeldsen and Plagenhoef. Similarly, the head and upper trunk mass values were compared, as they exhibited the greatest disparity with those previously established means. The established mass values reported by Zatsiorsky and Seluyanov (1981) were lower trunk (27.501%), thigh (14.165%), head, including the neck (6.94%) and upper trunk (15.955%). The lower trunk value in this study was found to be substantially less massive while the upper trunk was found to be more massive. Population specific differences between males and females, and the reported size differences, were most likely responsible for these discrepancies. The existance of the breasts in the upper trunk segment of females probably served to increase the mass proportionality value of that segment.

The established mass values reported by Hatze (1980) were head (6.18%), trunk (computed from shoulders, abdomino-thoracic and abdomino-pelvic segments : 41.13%) and thigh (14.66%). The comparable values determined in this study were 6.3% for the head, 41.52% for the trunk (by combining the neck, upper and lower trunk) and 14.63% for the thigh. These values were noticably similar to those reported by Hatze (1980). The minor discrepancies were most likely reflective of individual, within subject differences rather than variability between subject populations. This explanation was feasible as the sample populations were assumed to be homogeneous.

The comparisons which have been made served to validate the newly generated body segment mass percentage values. Much of the disparity between various researcher's mean values was attributable to different definitions of segment boundaries. Where congruency in establishing segment boundaries existed between researchers, discrepancies between mean mass values were minimized. Where segment boundaries were similar and disparity between means still existed, differences probably reflected population specific attributes such as sex and/or body type.

To examine whether the population specific attribute of body type was significant in explaining variability in the data, group means were calculated for each of the three representative body types present in the original sample. The mean segmental proportionality values for endomorphs, mesomorphs and ectomorphs are presented in Table 5. One-way

Table 5

Ratio of Segment Masses to Total Body Mass-Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	4.65 (0.28)	7.00 (1.08)	7.20 (0.50)	A,B
Neck	2.20 (1.07)	2.66 (0.53)	2.91 (0.53)	
Upper trunk	18.58 (1.55)	17.52 (1.53)	16.70 (1.30)	
Lower trunk	23.22 (0.83)	19.66 (0.86)	20.99 (2.39)	A
Arm	2.82 (0.38)	2.92 (0.15)	2.80 (0.19)	
Forearm	1.43 (0.08)	1.84 (0.18)	1.61 (0.09)	A,C
Hand	0.49 (0.06)	0.61 (0.02)	0.69 (0.16)	B
Thigh	15.08 (0.93)	14.38 (0.70)	14.43 (1.27)	
Shank	4.75 (0.29)	5.39 (0.55)	5.20 (0.46)	
Foot	1.07 (0.11)	1.39 (0.11)	1.38 (0.23)	B

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph
C. Mesomorph/Ectomorph

analyses of variance, fixed effects models, were employed for each segments mass percentage value. As the assumptions of normality and homogeneity of variance were violated, the results of the analysis of variance procedures should be regarded with some tentativeness. The analysis of variance tables for masses are presented in Appendix C. When statistically significant differences were found between the group means ($p < .05$), Scheffe's post-hoc multiple comparisons test was used to determine exactly where the difference occured. The results of these comparisons are also shown in Table 5.

The results of these analyses showed that the head, hand, and foot segments of the endomorphs were significantly smaller, in terms of percentages of total body mass, than those values reported for the ectomorphic group. The head segment mean value for the endomorphs was also significantly smaller than that value for the mesomorphs. Similar findings were reported by Kjeldsen (1972) when values were compared between gymnasts (shoulders wider than hips) and non-gymnasts (hips wider than shoulders). The amount by which the excess fat increased the body mass of the endomorphic subjects was disproportionately related to the change in mass of their head, hand and foot segments. Hence, the small percentage values of these segments reflected this uneven deposition of subcutaneous fat throughout the body.

The mean mass value of the endomorphs lower trunk was found to be proportionally larger than that of the mesomorphs. Contrary results were reported by Kjeldsen; gymnasts had greater lower trunk mass proportionality values than non-gymnasts. The discrepancy in these finding was attributable to differences in trunk/thigh established boundaries. The hips, in this study, were included as part of the thighs whereas Kjeldsen included them as part of the lower trunk. Thus as endomorphs had greater mass at the hips than mesomorphs, the boundary established in this study resulted in increasing the percentage value for the lower trunk and decreasing the percentage value for the thigh. Indeed, no significant difference was found, in this study, between the thigh values of the two groups while Kjeldsen found the non-gymnast thigh value to be substantially larger than the gymnasts.

The final segment mass value found to exhibit a significant difference between the groups was that of the forearm. The mesomorph group's percentage mass value was significantly larger than either of the other two groups values. Kjeldsen also found the forearm mass to be proportionally greater in the gymnasts and suggested the difference could be due to the sport's specific training, known for its development of the upper body. Three of the four mesomorphs in this study were retired gymnasts, thus lending further support for the suggestion.

In the sample studied, the endomorph's component I was the most dominant defining component possessed. Thus suggesting that this group was more representative of a true endomorphic population than the other two were representative of their respective populations. The results previously discussed were consistent with this observation, in that differences in the segment mass percentage values principally existed between the endomorph/mesomorph and endomorph/ectomorph groups.

Segment Lengths

The segment length values obtained in this investigation are presented in Table 6. For comparison purposes, the pre-established values reported by Kjeldsen (1972) and Plagenhoef (1983) are similarly presented in Table 6. The length values were obtained by measuring directly from the photographs in this study, and directly from the subjects in the other reported studies. Hence any discrepancies not caused by reasons of measurement error and/or different estimated joint center locations, were reflective of individual and/or population specific differences. The segment length values for the head, neck,

Table 6

Ratio of Segment Lengths to Total Body Height

	Model Prediction		Kjeldsen (a)	Plagenhoef (b)
Segment	Mean	SD	Mean(c)	Mean
Head	10.79%	0.65(%)		10.75%(d,e)
Neck	6.63	1.09		
Upper trunk	15.78	1.35	30.05(f)	12.70
Lower trunk	15.52	1.01		17.40(g)
Arm	15.96	0.97	17.90	17.30
Forearm	15.22	0.73	16.40	16.00
Hand	10.32	0.45		5.75(d)
Thigh	25.98	1.31	24.90	24.90
Shank	25.23	0.87	25.40	25.00
Foot	11.70	0.40		4.25(d)

a. Kjeldsen,K. (1972)
b. Plagenhoef,S. (1963)
c. mean value of gymnasts and non-gymnasts
d. to center of gravity
e. includes the length of the neck
f. hip to shoulder
g. sum of abdomen and pelvis

hand and foot were presented, by Plagenhoef, as percentages to the center of gravity location. The foot and hand segments in this study were measured as the links extending from the proximal joint centers to the termination of the longest phalange. Similarly the head and neck segments were measured and recorded as the distance from the joint centers, expressed as a percentage of the total body height. Thus the values for these segments were not comparable with the previously established values. All other segment values were comparable as they were measured from similar estimated joint center locations, as defined by Dempster (1955). The total trunk length percentages were noticably similar. However, the proportional splits between upper and lower trunk were not similar. Plagenhoef reported substantially smaller upper trunk and larger lower trunk length values than were observed in this study. Assuming measurement error was negligable, these observed differences could have been reflective of differences common to each population. All other segment values were within 1.75% of at least one of the other reported means. These discrepancies were best e plained as either the result of population specific differences or individual differences.

Similar procedures and analyses that were utilized on the segment mass values were employed to establish the effect of varying body types on segment length percentage values. Table 7 presents the mean values for each of the groups as well as the results of the multiple comparisons procedures.

The ANOVA tables for differences among groups segment length, ratio values are presented in Appendix C. There were statistically significant differences ($p < .05$) between the length percentage values reported for the upper trunk segment. The endomorphic group's value was significantly larger than both the mesomorph and ectomorph trunk values. Thus the disparity between the upper trunk values presented in Table 6 was probably reflective of similar population specific characteristics.

The variability in the data for the forearm (see Table 6) could similarly be explained as resulting from population differences in body type. The forearm length mean percentage value was significantly greater in the mesomorphic group than in the endomorphic group. Contrary to these findings, Kjeldsen reported no differences between the forearm length percentage values of the two different body typed females.

The length percentage value of the head segment was found to be significantly larger for the mesomorphs than for either the ectomorphs or endomorphs.

All other segments failed to reject the null hypothesis at the .05 level. The resulting implication was that within

Table 7

Ratio of Segment Lengths to Total Body Height-Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	10.58	11.52	10.48	A, C
	(0.43)	(0.42)	(0.59)	
Neck	6.06	6.98	6.87	
	(1.55)	(0.74)	(0.76)	
Upper trunk	17.28	15.66	14.60	A, B
	(0.80)	(0.53)	(0.73)	
Lower trunk	15.81	15.14	15.55	
	(1.33)	(0.58)	(1.02)	
Arm	16.39	15.24	16.07	
	(0.92)	(0.94)	(0.89)	
Forearm	14.78	16.02	15.06	A
	(0.51)	(0.31)	(0.71)	
Hand	10.41	10.29	10.27	
	(0.57)	(0.41)	(0.45)	
Thigh	25.63	25.69	26.47	
	(1.21)	(0.95)	(1.62)	
Shank	23.37	23.56	22.95	
	(0.62)	(0.79)	(1.12)	
Foot	11.75	11.94	11.51	
	(0.26)	(0.38)	(0.46)	

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph
C. Mesomorph/Ectomorph

subject differences were principally the cause of the variability in the newly generated data, as well as in the previously established values.

Segmental Centers of Gravity

The mean locations of segment centers of gravity, expressed as percentages of segment length, are presented in Table 6. All values, including those reported by other investigators, were expressed with respect to the upper boundaries of the segments.

The center of gravity location values for the head, hand and foot segments were not comparable between investigators due to differently established boundaries. The head value reported by Plagenhoef included the neck, the hand center of gravity location was expressed as a percentage distance from the proximal joint center to the metacarpophalangeal joint and the foot value was expressed as a percentage of the distance measured from the calcaneous. The hand and foot values reported by Hall and DePauw (1982) were also not comparable as both segments were modelled as right triangular slices, thus the respective center of gravity values were fixed at 33.3% and 66.6%.

The values reported for the upper trunk were comparable based on their similar segmental boundaries. The value

Table 5

Location of Segment Center of Gravity
as a Percentage of the Segment Length

	Model Prediction		Hall & Depauw (a)	Plagenhoef (b)
Segment	Mean(c)	SD	Mean(c)	Mean(c)
Head	59.90%	2.06		55.00%(d)
Neck	56.41	2.60		
Upper trunk	53.67	2.20		56.30
Lower trunk	60.35	4.82	—	39.00(e)
Arm	45.90	3.84	41.90	45.80
Forearm	41.44	0.71	40.20	43.40
Hand	38.47	2.96	33.30	46.80
Thigh	43.95	1.88	40.00	42.80
Shank	40.74	1.04	43.40	41.90
Foot	38.25	1.86	66.70	50.00

a. Hall, S. and Depauw, K. (1982)
b. Plagenhoef, S. (1963)
c. as measured proximally
d. includes both the head and neck
e. sum of abdomen and pelvis

reported by Plagenhoef had the center of gravity of this segment more distal than the value generated from this study. The presence of breasts in the distal portion of this segment would tend to shift the center of gravity distally. Thus it could be speculated that the breast size of the subjects utilized in Plagenhoef's study was greater than that of the subjects used in the present investigation. This effect could be masked or magnified by the presence of exceptionally broad or noticably narrow shoulders. Thus the difference between the reported means could also have resulted from differences in shoulder width. As men generally exhibit broader shoulders than women, and are breastless, their center of gravity of the upper trunk should be situated more proximally. Indeed, Zatsiorsky and Selanuyov (1961) reported the center of gravity mean location for their sample of men to be 50.66% of the distance from the neck.

The values for lower trunk and thigh presented by Plagenhoef were not comparable because of differences in segment boundaries. The thigh value reported by Hall and Depauw (Table 6) placed the center of gravity of that segment more proximal than did the mean value reported from this study. This discrepancy was most likely reflective of the different collection techniques utilized. The elliptical zone technique used in the present study more adequately accounted for the shape fluctuations along the segment. Thus, assuming the discrepancy was not reflective of population specific differences, the true location of the center of gravity was probably more distal than that value reported by Hall and Depauw. Consistent with this observation was the center of gravity location of Hatze's (1980) female subject RM, 43.85% of the length as measured proximally. As was previously discussed, the weight characteristics of this subject were similar to the mean value reported in this study thus making their values somewhat comparable. The mean value for the center of gravity location of the thigh in Zatsiorsky and Seluyanov's sample was more distal (45.49%) than the newly established value for females. This finding was consistent with the normal perception of the differences between the male and female anatomy. Increased pelvic girdle size and additional subcutaneous fat depositions at the upper thigh served to shift the center of gravity more proximally in the female sample.

The remaining segments, the arm, forearm and shank, had predicted center of gravity locations within less than 1.25% of at least one of the other previously presented means. Similar results were presented by Hatze, for subject RM; arm 44.4, forearm 42.3 and shank 43.3% (average values calculated from both right and left segments).

The segment center of gravity location mean values for the different body typed subjects in this present investigation are reported, along with the results of the multiple comparisons procedures, in Table 9.

Large within subject variability was evident in the group means for several of the segments. Statistically significant differences between the locations of the centers of gravity were revealed for only two of the ten segments tested (Appendix C). The center of gravity of the arm segment was located significantly more distal in the endomorphs than for either of the mesomorphic or ectomorphic groups. This may have occured due to the excess depositions of subcutaneous fat along the segment, in endomorphs. Significant differences were found between all of the group values for the shank segment. The center of gravity location was found to be most proximal in endomorphs, next proximal in mesomorphs and most distal in ectomorphs. Possible reasons for these occurances may have included increased fat depositions around the knee in endomorphs and increased muscle mass around the belly of the gastrocnemius in the mesomorphs. Exhibiting neither of these characteristics along the shank would have resulted in the most distal location of the center of gravity, such as that which was evident among the ectomorphic subjects.

Table 9

Proximal Center of Gravity Locations expressed as Percentages of Segment Lengths- Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	60.87	58.27	60.17	
	(2.04)	(1.16)	(2.15)	
Neck	56.90	55.56	56.58	
	(2.50)	(1.39)	(3.44)	
Upper trunk	54.19	54.45	52.72	
	(3.50)	(0.71)	(1.31)	
Lower trunk	60.04	59.09	59.74	
	(7.70)	(2.96)	(2.82)	
Arm	49.62	44.13	43.98	A,B
	(3.10)	(4.12)	(1.63)	
Forearm	41.22	42.00	41.25	
	(0.40)	(0.59)	(0.86)	
Hand	36.82	37.71	40.35	
	(1.05)	(1.26)	(3.92)	
Thigh	43.99	43.90	43.95	
	(2.41)	(2.44)	(1.30)	
Shank	39.65	40.58	41.76	A,B,C
	(0.35)	(0.16)	(0.68)	
Foot	39.31	37.30	37.99	
	(0.93)	(1.44)	(2.42)	

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph
C. Mesomorph/Ectomorph

Segmental Radii of Gyration

Values for the moments of inertia about each of the three principal axes with respect to the segment centroid were obtained. The only comparable values in the literature were those obtained by Hatze (1980) on the 31 year old female subject. The demonstrated strong dependence of moment of inertia on stature and weight (Santschi et al, 1963) dictated the logical method of comparison. Subject M2 in this study (height 163.5 cm, weight 61 kg) most closely resembled the weight of Hatze's subject RM hence, was chosen for comparison. The computed moment of inertia values (in kg-m^2) about the transverse axis, passing through the mass centroid, for each comparable segment are subsequently presented. Those values for subject M2 and Hatze's RM (in brackets) were, for the head .0178 (.0209), right arm .0110 (.0118), right forearm .0052 (.0048), right hand .0006 (.0005), thigh .1137 (.1492), shank .0413 (.0505) and foot .0019 (.0027). The close correspondance between the aforementioned segmental values served to validate the newly generated data.

As the human body segments rotate about either the distal or proximal joint centers and not the center of mass, the moment of inertia values required for segmental analyses must be expressed with respect to those end points.

Similarly, these values are of interest because of their known critical dependence on the transfer, rather than on the local terms. Hence the parallel axis theorem was applied to the centroidal moment of inertia values to yield moment of inertia values about proximal and distal ends. Subsequent calculations resulted in the radii of gyration values expressed as percentages of total segment lengths.

Table 10 presents the segmental proximal and distal radii of gyration values, with respect to the transverse axes, determined in this study. Similarly, the only comparable values in the literature are likewise presented. The comparable segments, as previously discussed, between the two investigator's values were the arm, forearm and shank. The values reported for these segments were noticably similar thus further adding to the credibility of the method.

To examine whether the population specific attribute of body type significantly effected the radius of gyration values of females, group means were calculated for each of the representative groups in the sample. Tables 11 and 12 present the group mean values for segmental radii of gyration about the transverse axes through the proximal and distal joint centers respectively. Similarly presented in these tables are the results of the multiple comparisons procedures employed. The ANOVA tables are shown in Appendix

Table 10

Segmental Radii of Gyration- YY Transverse Axis
Percentages of Segment Lengths

	Model Prediction				Plagenhoef (a)	
	Proximal		Distal		Proximal	Distal
Segment	Mean	SD	Mean	SD	Mean	Mean
Head	70.35	2.30	54.95	1.10	61.00(b)	
Neck	71.39	4.60	62.61	6.40		
Upper trunk	62.90	2.40	57.23	2.30		
Lower trunk	72.81	4.40	58.83	4.60		
Arm	54.90	2.30	61.94	4.10	56.40	62.30
Forearm	48.81	1.00	63.84	0.90	53.00	64.30
Hand	45.05	3.00	65.93	2.00	54.90	
Thigh	52.66	1.50	63.73	2.00	53.50	65.80
Shank	49.06	1.00	65.75	1.00	51.40	65.70
Foot	44.53	1.90	67.06	1.80	69.00	60.00

a. Plagenhoef, S. (1983)
b. Head and Neck

Table 11

Proximal Radii of Gyration- Transverse Axis
Percentages of Segment Lengths
Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	71.44 (2.03)	68.33 (1.55)	70.80 (2.39)	
Neck	76.46 (4.27)	69.06 (1.54)	68.67 (1.86)	A,B
Upper trunk	63.73 (3.86)	63.47 (0.51)	61.84 (1.08)	
Lower trunk	75.11 (6.29)	71.61 (2.81)	71.69 (3.06)	
Arm	57.23 (1.56)	54.00 (2.65)	53.57 (1.04)	B
Forearm	48.11 (0.7[illegible])	49.35 (1.16)	49.03 (0.98)	
Hand	43.32 (1.30)	44.57 (1.66)	46.81 (3.82)	
Thigh	53.31 (2.12)	52.53 (1.38)	52.24 (1.04)	
Shank	47.75 (0.36)	49.06 (0.24)	50.01 (0.56)	A,B,C
Foot	45.75 (1.04)	43.51 (1.64)	44.21 (2.32)	

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph
C. Mesomorph/Ectomorph

Table 12

Distal Radii of Gyration- Transverse Axis
Percentages of Segment Lengths
Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	54.67 (1.61)	55.17 (0.64)	55.04 (0.91)	
Neck	66.23 (7.66)	60.59 (1.00)	59.25 (3.92)	B
Upper trunk	57.73 (3.69)	56.29 (1.03)	57.43 (1.38)	
Lower trunk	60.90 (7.06)	57.99 (2.04)	57.67 (3.27)	
Arm	57.99 (3.88)	64.03 (3.72)	63.83 (1.73)	A,B
Forearm	63.27 (0.96)	63.73 (0.35)	64.38 (0.77)	
Hand	67.13 (0.58)	66.19 (0.72)	64.76 (2.68)	
Thigh	64.53 (2.00)	63.39 (2.85)	63.30 (1.37)	
Shank	66.57 (0.57)	66.00 (0.20)	64.90 (0.84)	B
Foot	66.22 (1.06)	68.02 (1.21)	67.17 (2.48)	

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph

C. Different distributions of the masses about both centers of rotation were found between the groups for the neck, arm and shank segments. Variance between the ectomorph and endomorph group means was present for both proximal and distal values for each of the aforementioned segments. Similar differences were found between the endomorph and ectomorph groups for the proximal neck, proximal shank and distal arm radii of gyration values. The proximal shank value was also significantly different between the endomorph and mesomorph groups.

The model predicted values for the ratio of the radius of gyration about the anteroposterior or frontal axis of the segment to the length of the segment are presented in Table 13. No values were available in the literature for comparisons. The values were similar to those presented for the transverse axis (Table 10) however, as the idealized segments were not symmetrical about their long axes, the values were not identical. Tables 14 and 15 show the group mean values for the radii of gyration percentage values for each of the modelled segments. Statistically significant differences, (see Appendix C), were evident between en o orphs and ectomorphs for the values of proximal and distal arm and shank, and distal upper trunk and hand segments. Similarly, differences were noted between the endomorph and mesomorph groups for the proximal shank and

Table 13

Segmental Radii of Gyration- XX Frontal Axis
Percentages of Segment Lengths

	Model Prediction			
	Proximal		Distal	
Segment	Mean	SD	Mean	SD
Head	68.19	2.30	51.89	1.58
Neck	71.35	4.47	61.80	4.83
Upper trunk	66.66	2.18	60.27	2.45
Lower trunk	71.55	4.04	68.26	4.21
Arm	54.06	2.47	61.81	4.13
Forearm	49.52	0.68	64.51	0.68
Hand	46.30	3.30	67.00	2.17
Thigh	51.85	1.92	63.32	1.93
Shank	48.64	1.05	65.74	0.93
Foot	36.95	1.83	43.14	2.33

Table 14

Proximal Radii of Gyration- Frontal Axis
Percentages of Segment Lengths
Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	69.40 (2.30)	66.27 (1.37)	68.47 (2.24)	
Neck	74.99 (4.66)	69.04 (1.73)	69.87 (4.07)	
Upper trunk	66.77 (3.83)	67.09 (1.17)	66.27 (0.63)	
Lower trunk	69.44 (5.23)	72.35 (3.39)	72.78 (3.18)	
Arm	56.36 (2.19)	53.40 (2.52)	52.58 (1.09)	[illegible]
Forearm	49.27 (0.33)	50.01 (0.69)	49.42 (0.80)	
Hand	44.71 (1.25)	45.63 (1.42)	48.09 (4.62)	
Thigh	51.58 (2.91)	52.33 (1.52)	51.75 (1.36)	
Shank	47.43 (0.55)	48.78 (0.41)	49.56 (0.52)	A,B
Foot	37.73 (1.28)	35.90 (2.15)	37.00 (1.95)	

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph

Table 15

Distal Radii of Gyration- Frontal Axis
Percentages of Segment Lengths
Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	52.02 (2.16)	52.50 (0.88)	51.38 (1.49)	
Neck	65.10 (6.39)	60.82 (2.85)	59.70 (3.28)	
Upper trunk	58.33 (2.72)	60.11 (0.98)	62.00 (1.72)	B
Lower trunk	71.12 (5.78)	68.06 (3.00)	66.03 (1.82)	
Arm	57.77 (3.54)	63.92 (4.05)	63.76 (1.86)	A, B
Forearm	64.64 (0.46)	64.05 (0.56)	64.71 (0.83)	
Hand	68.52 (1.39)	67.53 (1.19)	65.38 (2.27)	B
Thigh	64.04 (2.06)	62.90 (2.74)	63.00 (1.34)	
Shank	66.66 (0.46)	65.79 (0.26)	64.93 (0.75)	B
Foot	43.14 (2.46)	41.96 (3.55)	43.94 (0.99)	

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph

distal arm segment values.

The final parameter obtained from the computerized mathematical model utilized in this study were the percentage values of the radius of gyration about the longitudinal axis. Table 16 presents the aforementioned computed values for each of the body segments along with comparable values reported in the literature. In arriving at these values, no transfer terms were existant thus, as would be expected, the values were noticably smaller than those reported for the transverse and anteroposterior axes (Tables 10 & 13). Also, as the distribution of the mass relative to the long axis of the segment was reflective of the thickness of that segment, the expected resulting values would largely be dependent on the size of the subjects sampled. Indeed, the values reported by Zatsiorsky and Seluyanov (1981) were larger than those obtained in the present investigation as the mean size of the male subjects studied was larger than the mean size of the females utilized in this study. Taking this into consideration, the newly established values were similar enough to those pre-established values to be accepted as credible.

The notion that body size was significant in explaining the differences of the values of the radius of gyration about the long axis was further supported by the values presented in Table 17. The group means for each segment

Table 10

Segmental Radii of Gyration— ZZ Longitudinal Axes
Percentages of Segment Lengths

Segment	Model Prediction Mean	Model Prediction SD	Zatsiorsky & Seluyanov (a) Mean
Head	33.21	1.58	
Neck	46.91	10.59	
Upper trunk	35.40	1.42	46.50
Lower trunk	33.12	5.62	
Arm	12.5[illegible]	1.93	18.20
Forearm	10.17	1.25	13.00
Hand	13.38	1.57	18.20
Thigh	13.59	2.25	12.10
Shank	9.72	1.10	11.40
Foot	17.50	0.96	12.40

a. Zatsiorsky, V. and Seluyanov, V. (1981)

Table 17

Radii of Gyration- Longitudinal Axis
Percentages of Segment Lengths
Group Means

Segment	Endomorphs (n=5) Mean (SD)	Mesomorphs (n=4)	Ectomorphs (n=6)	Scheffe Comparisons *
Head	33.86 (1.55)	31.77 (1.05)	33.63 (1.44)	
Neck	57.56 (12.5)	42.50 (3.24)	40.99 (3.27)	A,B
Upper trunk	36.72 (0.51)	35.03 (1.28)	34.55 (1.30)	B
Lower trunk	39.70 (4.00)	32.00 (2.20)	28.37 (1.16)	A,B
Arm	14.39 (0.87)	13.04 (0.96)	10.58 (1.00)	B,C
Forearm	11.67 (0.29)	9.84 (0.59)	9.15 (0.72)	A,B
Hand	13.80 (1.09)	13.49 (0.73)	12.97 (2.29)	
Thigh	16.15 (1.57)	13.36 (0.38)	11.60 (0.88)	A,B
Shank	10.91 (0.77)	9.62 (0.21)	8.80 (0.66)	A,B
Foot	18.26 (0.57)	17.85 (0.93)	16.62 (0.41)	B,C

* significant at .05
A. Endomorph/Mesomorph
B. Endomorph/Ectomorph
C. Mesomorph/Ectomorph

were tested for significance (see Appendix C). All segments with the exception of the head and hand were found to have significantly different percentage values for radii of gyration about the longitudinal axes. The results of the multiple comparisons procedures are also shown in Table 17. All reported segment values were found to be different between the endomorphs and ectomorphs. Similarly, differences were found between the endomorphs and mesomorphs for the values of the neck, lower trunk, forearm, thigh and shank. Significant differences were also reported for the arm and foot segment values between mesomorphs and ectomorphs. As was previously discussed, the clear distinction between the endomorphs and the other groups, most notably the ectomorphs, resulted in principal differences occuring, for the reported parameters, between these respective group means.

Summary

In summary, the body segment characteristics of 15 female subjects were obtained, via the Jensen mathematical modelling technique, and studied. Results revealed expected congruency with previously reported data. Apparent discrepancies were explainable due to a variety of factors. Between group comparisons located some significant differences in the size and inertial parameter values between the representative body types. Principal differences occured between the endomorph/ectomorph and endomorph/mesomorph groups.

Chapter V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to establish a complete set of body segment parameter data for college age females of different body types.

Fifteen undergraduate and graduate students were used as subjects. The Heath-Carter (1967) method of somatotyping was utilized to classify subjects according to body type. Predominance of one of the components in the rating scale was used as the criterion for deeming subjects as being either endomorphic, mesomorphic or ectomorphic. Once classified, subjects were photographed, with relevant anatomical landmarks and joint centers marked, in two planes (x-z, y-z).

A photogrammetric mathematical model, previously proposed by Jensen (1976), was used to determine the size and inertial parameters of interest. Each segment of this 16-segment model was assumed to be composed of serial, horizontal elliptical zones, two centimeters wide. Hence the required input parameters were obtained by digitizing the endpoints of each elliptical zone.

Data obtained from the computerized model, written in Fortran IV, included segmental masses, segmental lengths, locations of segmental centers of gravity, and the values for proximal and distal segmental radii of gyration locations about each of the three principal axes. These body segment parameter data were presented in percent ratio form.

The overall accuracy of the model for determining total body mass of females was found to be better than 99%.

To validate the newly generated body segment data, selected values were compared with those available in the literature. Sufficient congruency was evident between pre-established norms and model-predicted parameters to further establish the credibility of the model.

Where disparity between various researcher's mean values was apparent, the discrepancy was often attributable to population specific differences. Other factors such as different data collection techniques and different segmental boundary definitions were also found to create disparity between reported values.

To examine whether the population specific attribute of body type was significant in explaining variability in the data, group means were calculated for each of the three representative body types present in the original sample. One way analyses of variance were employed for each predicted segmental parameter. When statistically significant differences were found between the group means ($p < .05$), Scheffe's post-hoc multiple comparisons test was used to determine the exact location of the difference.

Some significant differences in parameter values were revealed between the endomorph, mesomorph and ectomorph body types. These differences occured primarily in the computed percentage values of segment mass and radius of gyration about the longitudinal axes. The observed differences principally existed between the endomorph/ectomorph and endomorph/mesomorph groups. These findings were consistent with expectations, as the degree to which the endomorphs exhibited characteristics of fatness by far exceeded the predominant characteristics possessed by either of the other two groups.

Conclusions and Recommendations

Based on the results obtained in this study, several conclusions and recommendations were warranted.

The credibility of the Jensen (1976) mathematical model for determining segmental size and inertial parameters of females was established. This method was found to provide a relatively fast and accurate means of obtaining segment parameter values not readily available from other sources.

In situations when direct application of the model is not feasible, it was recommended that the percent ratio values presented in the body of this paper be utilized to estimate the required parameters for subjects. Where significant differences were found to exist between group (based on body type) means, the appropriate values to be used should correspond with the body types of the subjects. For estimation of those parameter values that failed to reach significance between groups, the group means of the Heterogeneous sample ($\bar{X}$=15) should be employed. Where multiple comparisons procedures revealed significant differences between only one or two group means, a combination of either two or three group means should be utilized for the values which failed to reach significance. The body segment parameter values presented in this paper were intended for use with college age females exhibiting similar body characteristics to those subjects studied. Application of this data to other populations would not be recommended.

The unavailability of extreme body types from the population resulted in a relatively lax criterion adopted for accepting subjects as representative. It is the author's contention that had greater distinctions existed between the representative body types, more segment parameter values would have proven to be significantly different between groups. Similarly, adding to this concern was the relatively small sample size studied. An increased sample size would have served to more adequately represent the populations of interest, hence true differences between groups would have become more apparent.

Recommendations for Future Studies

The difficulty in validating body segment parameter data was apparent. Ideally values should have been compared with those determined experimentally however these methods were not feasible for various reasons. The level of accuracy attained by the mathematical model employed in this study was considered good by the author. If a similar study of this nature was to be undertaken, some recommendations, based on the author's experiences, should be considered.

1. Increase the sample size and include more extreme representative body types for the reasons previously stated.

2. Incorporate density values specifically determined for females, when such values become available.

3. Photograph the subjects from as far away as possible to minimize perspective error and thus reduce the number of required conversion constant values.

4. Adopt acceptable criteria for delineating the segments, consistent with methods reported in the literature, to allow comparisons between reported parameter values.

Importance of the Study

The results of this study have important implications for future biomechanics research on females. The established credibility of the Jensen model make it a viable option for estimating the body segment parameters directly from female subjects. In situations when direct application of the model is not feasible, the use of the newly generated body segment parameter ratio values is recommended. The recommended ratio values for estimating the required segment parameters are presented in Tables 18-25. Specific notes corresponding to the values calculated specifically for these tables are given. All other values were previously presented in the text and are either the heterogeneous group

Table 16

Recommended Ratio Values for Determining Segmental Masses *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	4.65	7.12(b)	7.12(b)
Neck	2.60	2.60	2.60
Upper trunk	17.54	17.54	17.54
Lower trunk	23.22	19.66	21.38(d)
Arm	2.84	2.84	2.84
Forearm	1.53(c)	1.84	1.53(c)
Hand	0.49	0.60(d)	0.69
Thigh	14.63	14.63	14.63
Shank	5.10	5.10	5.10
Foot	1.07	1.28(d)	1.38

* Expressed as percentages of total body mass
b. mean of mesomorph and ectomorph groups
c. mean of endomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

Table 19

Recommended Ratio Values for Determining Segmental Lengths *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	10.52(c)	11.52	10.52(c)
Neck	6.63	6.63	6.63
Upper trunk	17.28	15.03(b)	15.03(b)
Lower trunk	15.52	15.52	15.52
Arm	15.96	15.96	15.96
Forearm	14.78	16.02	15.22(d)
Hand	10.32	10.32	10.32
Thigh	25.98	25.98	25.98
Shank	23.23	23.23	23.23
Foot	11.70	11.70	11.70

* Expressed as percentages of total body height
b. mean of mesomorph and ectomorph groups
c. mean of endomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

Table 20

Recommended Ratio Values for Determining Proximal Center of Gravity Locations *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	59.90	59.90	59.90
Neck	56.41	56.41	56.41
Upper trunk	53.67	53.67	53.67
Lower trunk	60.33	60.33	60.33
Arm	49.62	44.04(b)	44.04(b)
Forearm	41.44	41.44	41.44
Hand	38.47	38.47	38.47
Thigh	43.95	43.95	43.95
Shank	39.65	40.56	41.76
Foot	38.25	38.25	38.25

* Expressed as percentages of segment lengths
b. mean of mesomorph and ectomorph groups

Table 21

Recommended Ratio Values for Determining Proximal Radius of Gyration Locations about Transverse Axes *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	70.40	70.40	70.40
Neck	76.46	68.82(b)	68.82(b)
Upper trunk	62.90	62.90	62.90
Lower trunk	72.80	72.80	72.80
Arm	57.23	54.90(d)	53.57
Forearm	46.80	48.80	48.80
Hand	45.10	45.10	45.10
Thigh	52.70	52.70	52.70
Shank	47.92	49.06	50.01
Foot	44.50	44.50	44.50

* Expressed as percentages of segment lengths
b. mean of mesomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

Table 22

Recommended Ratio Values for Determining Distal Radius of Gyration Locations about Transverse Axes.*

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	54.90	54.90	54.90
Neck	68.25	62.60(d)	59.25
Upper trunk	57.20	57.20	57.20
Lower trunk	58.80	58.80	58.80
Arm	57.99	63.91(b)	63.91(b)
Forearm	63.80	63.80	63.80
Hand	65.90	65.90	65.90
Thigh	63.70	63.70	63.70
Shank	66.57	65.70(d)	64.90
Foot	67.10	67.10	67.10

* Expressed as percentages of segment lengths
b. mean of mesomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

Table 23

Recommended Ratio Values for Determining Proximal Radius of Gyration Locations about Frontal Axes *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	68.19	68.19	68.19
Neck	71.35	71.35	71.35
Upper trunk	66.66	66.66	66.66
Lower trunk	71.55	71.55	71.55
Arm	56.36	54.06(d)	52.56
Forearm	49.52	49.52	49.52
Hand	46.30	46.30	46.30
Thigh	51.85	51.85	51.85
Shank	47.43	49.25(b)	49.25(b)
Foot	36.95	36.95	36.95

* Expressed as percentages of segment lengths
b. mean of mesomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

Table 24

Recommended Ratio Values for Determining Distal Radius of Gyration Locations about Frontal Axes *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	51.89	51.89	51.89
Neck	61.80	61.80	61.80
Upper trunk	58.33	60.27(d)	62.00
Lower trunk	68.26	68.26	68.26
Arm	57.77	63.82(b)	63.82(b)
Forearm	64.51	64.51	64.51
Hand	68.52	67.00(d)	65.38
Thigh	63.32	63.32	63.32
Shank	66.66	65.74(d)	64.93
Foot	43.14	43.14	43.14

* Expressed as percentages of segment lengths
b. mean of mesomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

Table 25

Recommended Ratio Values for Determining Radius of Gyration Locations about Longitudinal Axes *

Segment	Endomorphs	Mesomorphs	Ectomorphs
Head	33.21	33.21	33.21
Neck	57.56	41.59(b)	41.59(b)
Upper trunk	36.72	35.40(d)	34.55
Lower trunk	39.70	29.82(b)	29.82(b)
Arm	13.79(a)	13.79(a)	10.58
Forearm	11.67	9.43(b)	9.43(b)
Hand	13.38	13.38	13.38
Thigh	16.15	12.31(b)	12.31(b)
Shank	10.91	9.13(b)	9.13(b)
Foot	18.09(a)	18.09(a)	16.62

* Expressed as percentages of segment lengths
a. mean of endomorph and mesomorph groups
b. mean of mesomorph and ectomorph groups
d. mean of endomorph, mesomorph and ectomorph groups

mean ($\bar{x}$=15) or a specific group's mean (endomorph, mesomorph or ectomorph). These tables are based on found statistically significant differences from the ANOVA procedures performed. As the assumptions of analysis of variance have been violated, the more conservative reader may chose to use the mean values ($\bar{x}$=15) presented in the text.

The three sets of data presented fill the void which existed in terms of data on females of different body types. Provided the inherent limitations are recognized, the use of the newly generated data is warranted.

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APPENDIX A

INFORMED CONSENT FORM

Faculty of Human Kinetics
Biomechanics Research Laboratory

Consent Form

Project Title

Body Segment Parameter Determination in College-age Women

Project Outline

The testing process will include tests which do not necessitate physical exertion or any form of deception.

An anthropometric somatotype rating will be determined for each subject using the Heath-Carter method. Figure 1 illustrates the measurements required for its determination. Included are age, height, weight, skinfolds (triceps, subscapular, supraspinale, calf), bone diameters (humerus, femur) and muscle girths (flexed arm, calf).

Body segment parameters will be obtained using a photogrammetric mathematical model. Subjects will be photographed, in two planes (X-Z, Y-Z), wearing a light bathing suit and bathing cap. Relevant anatomical landmarks and joint centers will be marked to facilitate the digitizing procedure (Fig.2).

Participation and Confidentiality

Participation in any or all of the tests is voluntary and subjects are free to withdraw at any point during the testing session. Information collected on specific subjects will be kept confidential and any data published or otherwise disseminated will be grouped and will not include any identifying information.

Subject Consent

Name ______________________________

Researcher(s) ______________________________

I know the purpose of the sessions and consent to take them of my own free will understanding the information will be handled in a professional and ethical manner. I agree to participate.

____

Signature Date

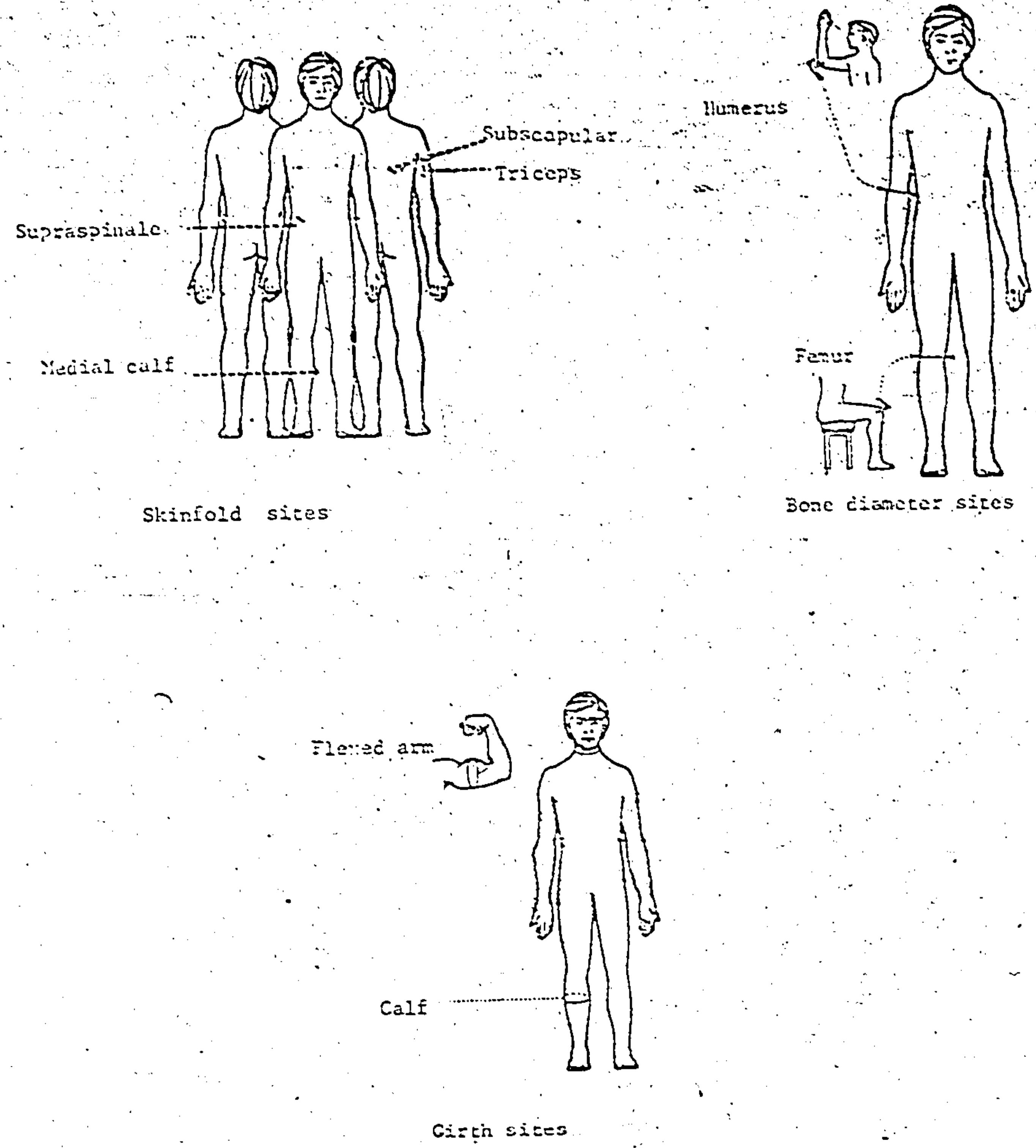


Figure 1. Measurement sites for determination of somatotype rating (Figures from Ross & Marfell-Jones, 1982).

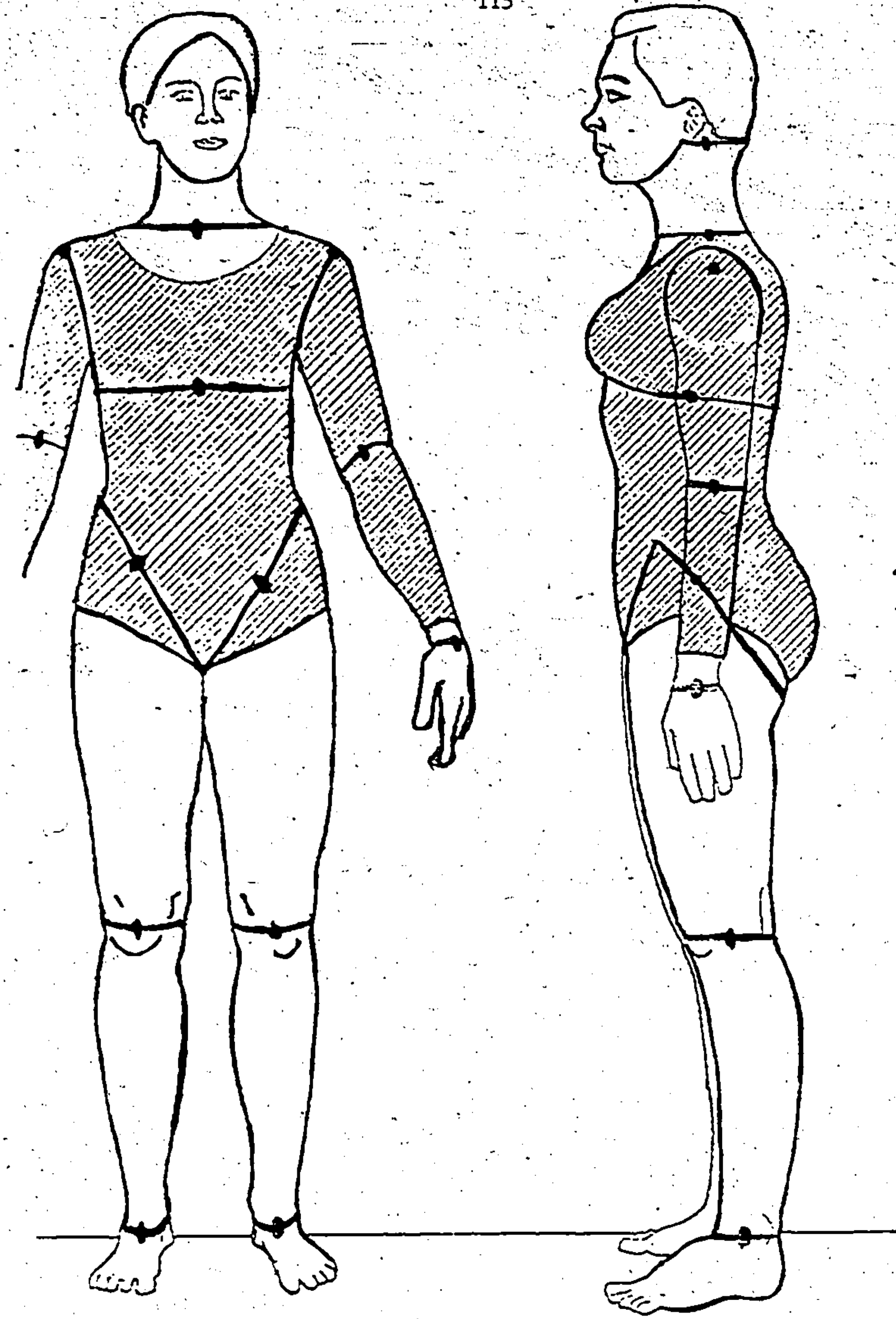
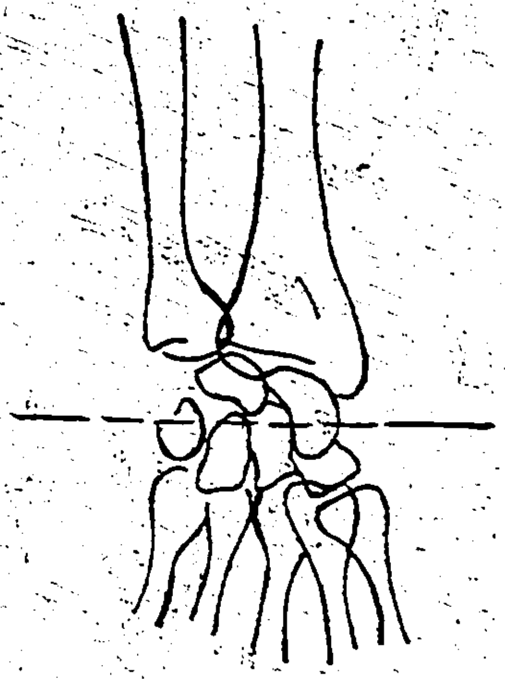


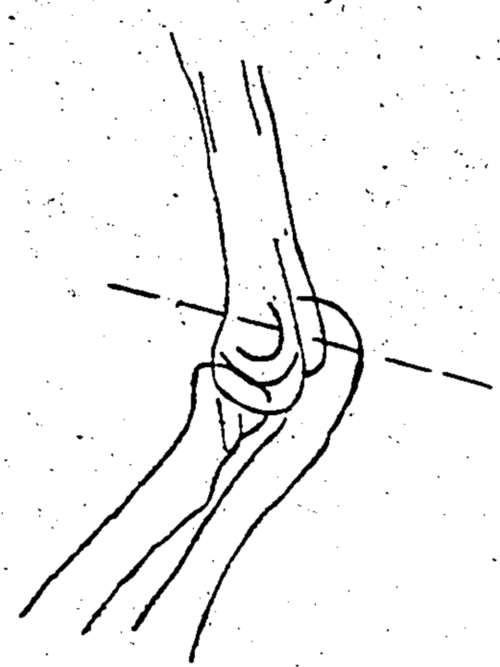
Figure 2. Relevant anatomical landmarks and joint centers (Figure from Kjeldsen, 1972).

APPENDIX B

JOINT SEGMENTATION ILLUSTRATIONS

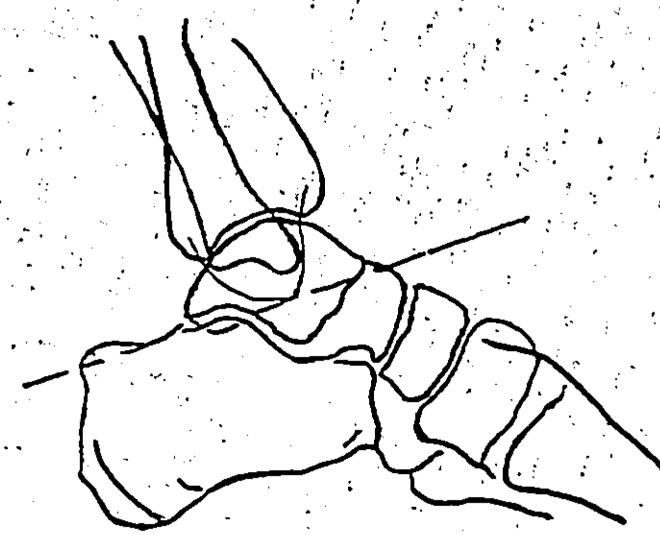


Wrist Segmentation (figure from Kjeldsen, 1972)

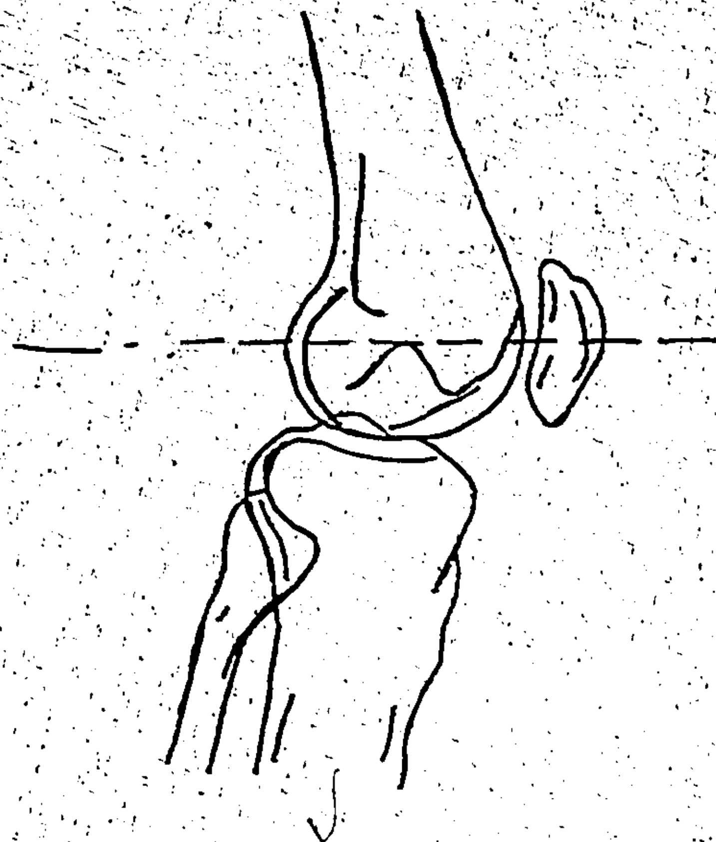


Elbow Segmentation (figure from Kjeldsen, 1972)

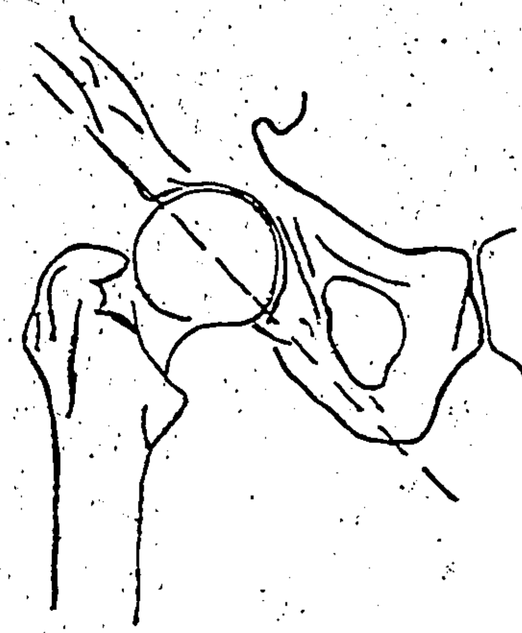
Shoulder Segmentation (figure from Kjeldsen, 1972)



Ankle Segmentation (figure from Kjeldsen, 1972)



Knee Segmentation (figure from Kjeldsen, 1972)



Hip Segmentation (figure from Kjeldsen, 1972)

APPENDIX C

ANALYSIS OF VARIANCE TABLES FOR ALL DEPENDENT VARIABLES

ANOVA Table: Segment Masses (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00102602	.00004198	24.44	.0001
Neck	.00006926	.00005670	1.22	.3289
Upper trunk	.00048181	.00020909	2.30	.1423
Lower trunk	.00147831	.00027848	5.31	.0223
Arm	.00000204	.00000696	0.29	.7512
Forearm	.00001873	.00000139	13.49	.0009
Hand	.00000567	.00000118	4.80	.0295
Thigh	.00007598	.00010841	0.70	.5154
Shank	.00005016	.00001922	2.61	.1146
Foot	.00001624	.00000297	5.47	.0205

ANOVA Table: Segment Lengths (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00014748	.00002496	5.91	.0163
Neck	.00012196	.00011756	1.04	.3841
Upper trunk	.00097891	.00005077	19.28	.0002
Lower trunk	.00005019	.00011047	0.45	.6453
Arm	.00015375	.00008343	1.84	.2005
Forearm	.00018296	.00003202	5.71	.0181
Hand	.00000293	.00002338	0.13	.8833
Thigh	.00011821	.00018093	0.65	.5379
Shank	.00004952	.00008034	0.62	.5561
Foot	.00002229	.00001474	1.51	.2596

ANOVA Table: Segment Center of Gravity Location (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00078940	.00036450	2.17	.1574
Neck	.00021338	.00075130	0.28	.7577
Upper trunk	.00045839	.00048646	0.94	.4168
Lower trunk	.00114480	.00252468	0.45	.6459
Arm	.00519553	.00085747	6.06	.0152
Forearm	.00008429	.00004480	1.88	.1947
Hand	.00185623	.00071537	2.59	.1157
Thigh	.00000094	.00041258	0.00	.9977
Shank	.00061326	.00002389	25.67	.0001
Foot	.00048222	.00032515	1.48	.2657

ANOVA Table: Radius of Gyration Location-YY Proximal (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00117572	.00043616	2.70	.1079
Neck	.00973426	.00081115	12.00	.0014
Upper trunk	.00057551	.00055108	1.04	.3818
Lower trunk	.00198332	.00190454	1.04	.3828
Arm	.00205354	.00030150	6.81	.0106
Forearm	.00019451	.00009098	2.14	.1606
Hand	.00172487	.00073280	2.35	.1373
Thigh	.00016227	.00024140	0.67	.5288
Shank	.00059489	.00001874	31.75	.0001
Foot	.00061171	.00032743	1.87	.1966

ANOVA Table: Radius of Gyration Location-YY Distal (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00003101	.00013105	0.24	.7929
Neck	.01214407	.00273447	4.44	.0360
Upper trunk	.00025155	.00056043	0.45	.6487
Lower trunk	.00161609	.00222254	0.73	.5034
Arm	.00584780	.00097219	6.02	.0155
Forearm	.00016947	.00005868	2.89	.0946
Hand	.00078608	.00032229	2.44	.1292
Thigh	.00023820	.00041300	0.58	.5766
Shank	.00039848	.00004116	9.68	.0031
Foot	.00036380	.00033122	1.10	.3647

ANOVA Table: Radius of Gyration Locations-XX Proximal (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00112902	.00043151	2.62	.1140
Neck	.00503112	.00149091	3.37	.0687
Upper trunk	.00008578	.00053985	0.16	.8548
Lower trunk	.00169453	.00162226	1.04	.3818
Arm	.00207118	.00036780	5.63	.0188
Forearm	.00006597	.00004234	1.56	.2503
Hand	.00167925	.00099173	1.69	.2250
Thigh	.00006772	.00041849	0.16	.8524
Shank	.00062308	.00002582	24.13	.0001
Foot	.00037335	.00032836	1.14	.3530

ANOVA Table: Radius of Gyration Locations-XX Distal (df=2,12)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00015479	.00026649	0.58	.5744
Neck	.00424298	.00201032	2.11	.1639
Upper trunk	.00184061	.00039405	4.67	.0316
Lower trunk	.00354738	.00147472	2.41	.1323
Arm	.00609927	.00097263	6.27	.0137
Forearm	.00005835	.00004375	1.33	.2999
Hand	.00142163	.00031417	4.53	.0343
Thigh	.00019759	.00040387	0.49	.6248
Shank	.00040801	.00003219	12.67	.0011
Foot	.00046888	.00055638	0.84	.4545

ANOVA Table: Radius of Gyration Locations- ZZ (df=2,14)

Segment	MS(b)	MS(w)	F-ratio	PR>F
Head	.00058210	.00019342	3.01	.0872
Neck	.04276035	.00595119	7.19	.0089
Upper trunk	.00068067	.00012030	5.66	.0186
Lower trunk	.01783765	.00071018	25.12	.0001
Arm	.00205585	.00008971	22.92	.0001
Forearm	.00089639	.00003310	27.06	.0001
Hand	.00009714	.00027179	0.39	.7067
Thigh	.00283991	.00011813	24.04	.0001
Shank	.00061226	.00003906	15.67	.0005
Foot	.00040860	.00003930	10.40	.0024

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Marino, G.W., Finch, C.A. and Duthie, J.H.(1985). Analysis of Selected Gait Characteristics in Three Functional Groupings of Older Adults. In D.A. Winter, R.W. Norman, R.P. Wells, K.C. Hayes and A.E. Patla (Eds.), Biomechanics 9A (pp 468-472). Champaign, Ill: Human Kinetics.

Marino, G.W., Finch, C.A. and Young, W. (1984). Variation in Walking Movements in Older Adults. In A.B. Thornton-Trump (Ed.), Human Locomotion III: Proceedings of Third Biannual Conference for Canadian Society of Biomechanics (pp 61-62)